SIMULATION OF ACTIVE HYBRID FILTER

By

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SIMULATION OF ACTIVE HYBRID FILTER

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by

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CERTIFICATE

This is certified that the work contained in this thesis entitled, "**Simulation of Active Hybrid Filter**", by **Shinde Satish Mahadev**, has been carried out under my supervision and this work has not been submitted elsewhere for a degree.

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ABSTRACT

Proliferation of non-linear devices like ASDs has resulted in serious utility interface issues. These devices degrade power quality by distorting voltage and current waveforms, drawing reactive power and causing voltage flicker. The distortion of current or voltage waveform is expressed in terms of harmonics. Utilities are facing problems due to harmonics such as higher losses, resonance and due to this equipment derating is required. Apart from increase in losses, harmonics also cause malfunctioning of equipment. Passive filters consisting of capacitors and inductors have long been used to reduce harmonics. Passive filters offer less expensive and simple solution to the harmonics. But passive filters suffer from the danger of resonance at one or more harmonic frequency, which further increases harmonics. Active filters overcome majority of the drawbacks of the passive filters. Pure active filters provide effective solution for a small rating nonlinear load, but are not feasible and cost effective for a large rated non-linear load due to their high rating requirement. Hybrid filters offer a cost effective and practical solution for harmonic filtering and harmonic isolation for large rated nonlinear loads. In this scheme small rated square wave inverter switching at dominant harmonic frequency is transformer coupled to each L-C branch of the passive filter to form the hybrid parallel active filter system. This system employs low rating low switching frequency square wave inverters to achieve harmonic isolation at dominant harmonic frequencies. Active tuning commands for the passive filter is calculated in d-q reference frame. Modified PWM scheme is used to generate desired voltage from inverter of the active filter. This scheme will overcome limitations of pure passive filters such as component tolerances, component variation resulting from aging, temperature rise, and out of specification inductors, change in capacitance value due to capacitor bank unit failures. The scheme is validated by simulating it using EMTDC/PSCAD software. IEEE 519-1992 limits are checked at PCC with active hybrid filter.

This Thesis Work Is Dedicated To My Alma Mater

I.I.T. Kanpur

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CONTENTS

CHAPTER 1

INTRODUCTION

The use of adjustable speed drives (ASDs), uninterruptible power supply (UPS), and rectifiers is increasing rapidly in industrial processes. Adjustable speed drives are preferred because of increase in productivity and energy efficiency. But benefits of ASDs come at the cost of pollution of power system in the form of harmonics. UPS systems that are used for protecting computers and other sensitive loads also pollute power systems. The systems like ASD, UPS or rectifiers inject harmonics in power system. Utilities and consumers face lots of problems due to harmonics like increased losses, harmonic interaction between power factor correction capacitors. Many utilities have started enforcing harmonic related standards like IEEE 519 [1] particularly on large customers. There is seldom any initiative from a customer to meet these standards, as there is no direct benefit (like immediate increase in production or profit) to the customer. This implies that solution to harmonics should be very cost effective. In this thesis a cost-effective scheme for harmonic reduction – Hybrid Active filter is discussed for high power applications. One case is simulated and results are discussed for the same.

Harmonic is a sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency. Harmonics produced by semiconductor converter equipment in the normal course of operation are called characteristic harmonics. Harmonics produced due to beat frequencies, imbalance cycloconverter operation or asymmetrical delay angle are called as non-characteristic harmonics.

Severity of harmonics is generally quantified by an index Total Harmonic Distortion or better known as THD. Let V_i (for i = 2, 3, ...n) be the harmonic components of a voltage waveform that has fundamental component of V_1. Then THD is defined as

$$THD_V = \frac{\left[\sum_{i=2}^{n} V_i^2\right]^{1/2}}{V_1} \tag{1.1}$$

Similarly for current the THD is defined as

$$THD_I = \frac{\left[\sum_{i=2}^{n} I_i^2\right]^{1/2}}{I_1} \tag{1.2}$$

1.1. SOURCES OF HARMONICS

Non-linear devices are the sources of harmonics. These can be classified as

Traditional types:

- Transformers
- Rotating machines
- Arc furnaces
- Fluorescent lights.

Power electronic type:

- Electronic controls and switched mode power supplies
- Thyristor controlled devices
- Rectifiers
- Inverters
- Static VAR Compensators
- Cycloconverters
- HVDC transmission.

Power transformers are the sources of harmonics since they use magnetic materials that are operated very close to and often in the nonlinear region for economic purposes. This results in the transformer magnetizing current being non-sinusoidal and containing harmonics (mainly third) even if the applied voltage were sinusoidal. The converse is also true. If the magnetizing current were sinusoidal, the voltage could not be so. Rotating machines are considered sources of harmonics because the windings are embedded in slots, which can never be exactly sinusoidally distributed so that mmf wave is distorted. Generally harmonics produced by rotating machines are considered as negligible compared to those produced by the other sources.

The harmonics produced by the arc furnaces used for the production of the steel are unpredictable because of the cycle by cycle variation of the arc, particularly when boring into new steel scrap. It contains both integer and non-integer harmonics. In fluorescent lamps voltage builds up in each half cycle till ignition occurs. The lamp then appears as a negative resistance, the current being limited by the non-linear reactive ballast. The current is thus distorted. Moreover electronic ballast used nowadays produces harmonics of patterns similar to and sometimes different from those produced by the older core and coil ballast.

In Static VAR compensators (and in general all other power electronic devices) the waveforms is modified in order to control the reactive power flow, this naturally give rise to harmonic injection. A cycloconverter converts ac power at a high frequency to one at a lower frequency. This converter topology generates both integer and non-integer harmonics. Most recent electronic equipment use switch mode power supply to provide the voltage to the equipment. It feeds a capacitor that supplies the voltage to the electronic circuitry. Since load is the capacitor as seen by the power system, the current to the power supplies is discontinuous. That is current flows only part of the half cycle. Nowadays large numbers of renewable and alternate energy sources, which use inverters for utility connection are finding place in power system network. These inverters also inject harmonics in the power system.

1.2. EFFECTS OF HARMONICS IN POWER SYSTEMS

The effects of voltage distortion could be divided into three categories.

- Thermal stress
- Insulation stress
- Load disruption.

Harmonics have the effect of increasing equipment losses and thus the thermal stress. Peak voltage is increased by harmonics. This results in the increased voltage or insulation stress. Load disruption is broadly defined as any device failure or abnormal operation caused by voltage distortion. Triplen harmonics i.e., the harmonics that are $3n$ (n = 1, 2, 3 ...) times the fundamental frequency result in the neutral carrying a current, which might equal or exceed the phase currents even if the load currents are balanced. This requires the derating or oversizing of the neutral wire [4]. Harmonics caused resonance might damage the equipment. Harmonics further interfere with customer electronic apparatus.

Capacitor offers low impedance to the higher harmonics, which results in overloading and blowing up of capacitor fuses. Capacitor can form resonant circuit with the system inductance leading to amplification of the harmonics. The harmonic order at resonance is

$$h_r = \frac{\omega_r}{\omega_0} = \frac{1}{\omega_0\sqrt{L_s C}} = \sqrt{\frac{X_C}{X_s}} = \sqrt{\frac{SCC}{Q_C}} \tag{1.3}$$

where, Q_C is the capacitor rating in MVAr and SCC is the bus short circuit capacity in MVA.

If harmonic producing load is more than 10 % and capacitor kVAr is more than 20 % then proper analysis has to be done before installing power factor correction capacitors. These guidelines are applicable when transformers with 5-6 % impedance are used and the system impedance behind the transformer is less than 1 % on the transformer base. ANSI/IEEE standard 18-2000 [2] indicates that the capacitor can be operated continuously within the following limitations, including harmonic components:

- 180 % of rated rms current
- 135 % of rated reactive power
- 110 % of rated rms voltage
- 120 % of rated peak voltage.

In transformers, the increase in the eddy current loss due to harmonics is more significant than hysteresis loss. Also there is a possibility of the resonance between power factor correction capacitors and the inductance of the transformer. Insulation is stressed due to the increased peak of the voltage. IEEE standard C57.12.00.1987 [10] poses the following limits on the transformers operating in a harmonic environment.

- Current THD should not exceed 5 %.
- Steady state RMS voltage should not exceed 110 % of rated at no load and 105 % of rated at rated load.

This is equivalent to saying that the voltage THD should not exceed $\sqrt{0.21} = 0.458$ at no load and $\sqrt{0.1025} = 0.32$ at rated load.

Pulsating torque is produced due to interaction of the harmonics generated magnetic fields and the fundamental in rotating machines. These result in higher audil le noise. Presence of harmonics in supply generates additional harmonics. Moreovei positive (4^{th}, 7^{th}, 10^{th}, 13^{th}, ...) and negative sequence (2^{nd}, 5^{th}, 8^{th}, 11^{th}, ...) harmonic ţ airs give rise to pulsating fields of frequencies $3 f_0$, $6 f_0$, $9 f_0$, $12 f_0$...respectively. Should the natural frequency of the generator be close to one of these frequencies, super-synchronous resonance would prevail accompanied by torsional oscillations and bending of the turbine shaft, and other mechanical systems. Negative sequence currents in generator appear as double frequency currents in the rotor circuit causing sever overheating [9].

Phase imbalance caused by harmonic distortion can cause erroneous operation of induction disk devices, such as watt-hour meters. In general distortion factor nas to be severe (i.e., greater than 20 %) before significant error can be detected.

As with other types of equipment harmonics increase heating and losses in the switchgear, which reduces its steady-state current carrying capability and shortening the life of some insulating components. Fuse rating has to be derated because of the extra heat produced by harmonics during normal operation. Ground relay can not distinguish between zero sequence and triplen harmonic currents. Relay response under distorted conditions may vary among relays having the same nominal fundamental frequency characteristics, not only among different relay manufacturers, but also among different vintages of relays from the same manufacturer [3].

The presence of harmonic currents or voltages in circuitry can produce electric and magnetic field that will impair the satisfactory performance of communication system that by the virtue of their proximity susceptibility can be disturbed. For a given physical arrangement this effect depends upon both amplitude and the frequency of the harmonic.

1.3. FILTERING OF HARMONICS

Filter is equipment used to reduce harmonic current or voltage contents in power system. Its effectiveness is determined by the amount of current it can allow through it compared to that flowing into system. The quality factor of filter determines the harmonic current flowing through the passive filter. Quality factor (Q) is the ratio of the impedance of the filter at tuned frequency to the resistance of the filter.

Harmonic filtering is done by providing low impedance path for the harmonic currents or by isolating the system from the harmonic-producing loads. Purpose of harmonic filters installed by individual customers is to compensate for the current harmonics produced by their own harmonic producing loads. Utilities provide filters for compensating the voltage harmonics or to provide damping. Passive filters that are combination of capacitors and inductors provide very economic solution for the harmonic filtering. Passive filter design involves high cost of engineering, as proper system study is required for its installation. One of the major issues in harmonic filter

design is resonance. Resonance phenomenon may takes place in a series or a parallel RLC circuit having equal inductive and capacitive reactances, such that circuit impedance is low and small exciting voltage results in a huge current.

Active filter, which consists of power electronic devices, provides black box solution to the harmonic filtering. It can be installed without much knowledge of the remaining system. Various active filter schemes have been proposed till date. Active filters are very costly and complex devices. Both active and passive filters are discussed in detail in Chapter 2.

Hybrid active filters contain active and passive filter thereby reducing the rating of active filter. Even though not a significant size reduction is obtained using these filters, they are much more flexible than passive filters.

1.4. OBJECTIVE OF THESIS

Passive filters are low cost and highly efficient solution for harmonic filtering but they are susceptible to series and parallel resonance with supply and load respectively. Also passive filter tolerances and utility system impedance variation due to changes occurring on the same feeder or neighboring feeders affect compensation characteristic of the passive filter. Stiff utility system makes the case even more difficult. Active filters do not suffer any of the above problems but they are very costly and in fact difficult to implement at very high power level.

Objective of this thesis is to determine a cost-effective scheme for harmonics reduction that combines passive and active filters. In this scheme a small rated inverter is connected in series with the passive filter. Small rating requirement leads to major cost reduction. Theory and control strategy for this scheme is developed. Using PSCAD/EMTDC Version 3.0 software package, the simulation results are produced to check the fulfillment of IEEE 519-1992 "IEEE recommended practices and requirements for harmonic control in power system" [1] at the Point of Common Coupling (PCC).

CHAPTER 2

MITIGATION OF HARMONICS

Various methods have been proposed to reduce harmonics. The oldest and widely used method is passive filters. Passive filters have their own limitations. Passive filters are suitable for very large load where there is no additional cost on system study and engineering as in such cases one already has correct knowledge of system parameters and its variations so there is no additional requirement of system engineering. Active filter installation does not require detailed system study but they are very costly. No matter which method is used solution should comply with the stated harmonic standard. In this chapter IEEE guidelines and IEC standard for power system harmonics are discussed. Passive filters active filters and hybrid active filters are also discussed in brief.

2.1 HARMONIC LIMITS

After carrying out harmonic analysis harmonic indices are compared with the referred standard. IEEE 519 is the most widely used standard for harmonic limits. IEC standards are also used in European countries. These two standards are discussed briefly in this Section.

2.1.1 IEEE 519-1992

IEEE 519 –1992 [1] standard is applicable to the point of common coupling (PCC). This standard gives guidelines separately for individual customer and utility.

2.1.1.1 Guidelines for Individual Customer

For individual customers the recommended harmonic indices are

1. Depth of notches, total notch area and distortion (RSS) of bus voltage by commutation notches (low voltage systems)
2. Individual and total harmonic distortion
3. Individual and total current distortion.

2.1.1.1.1 Limits on commutation notches

Total voltage distortion is proportional to total notch area. In low voltage system notch area can be measured and limits shown in Table 2.1 are given in IEEE 519-1992.

Table 2.1 Low voltage system commutation notch limits.

	Special Applications	General System	Dedicated System
Notch Depth	10 %	20 %	50 %
THD(Voltage)	3 %	5 %	10 %
Notch Area (in volt -microseconds)	16400	22800	36500

2.1.1.1.2 Current distortion limits

In IEEE 519-1992, the system is characterized by its short circuit impedance. Limits are made dependent on customer size. The customer size is expressed as the ratio of the short circuit current capacity at the customer's point of common coupling with the utility to the customer's maximum load (demand) current. The individual harmonic current limits are expressed in percent of this maximum load current. The objective of this standard is to limit the maximum individual harmonic voltage limit to 3 % of the fundamental and the voltage THD to 5 % for systems without a major parallel resonance. Harmonic current from various sources may have different phase angles. This leads to the addition of individual harmonic components less than their arithmetic sum. Also harmonic contents injected may vary over a period of time. These factors are taken into consideration while developing these limits. Basis for harmonic current limits is shown in Table 2.2.

Harmonic current distortion limits for a consumer are defined in Tables 2.3 to 2.5. TDD is total demand distortion (Root Sum Square), harmonic current distortion in the percent of maximum demand load current (15 or 30 minute demand). Figures listed in the following tables should be used as the design values for the "worst case" for normal

operation. For short duration these limits may be exceeded by 50%. It is recommended that load current be calculated as the average current of the maximum demand for the preceding 12 months. As the size of the user load decreases with respect to system size, the percentage of harmonic current that the user is allowed to inject into the utility system increases. This strategy protects other users on the same feeder as well as the utility.

Table 2.2 Basis for IEEE 519-1992 harmonic current limits.

SCR at PCC	Maximum Individual Frequency Voltage Harmonics (%)	Related Assumption
10	2.5-3.0 %	Dedicated system
20	2.0-2.5 %	1-2 large customers
50	1.0-1.5 %	A few relatively large customers
100	0.5-1.0 %	5-20 medium size customers
1000	0.05-0.10 %	Many small customers

All generation, whether connected to the distribution, subtransmission or transmission system is treated like utility distribution and is therefore held to these recommended practices.

Table 2.3 Current distortion limits for general distribution systems (120 V through 69 000 V).

I_{sc}/I_L	$h < 11$	$17 \geq h \geq 11$	$23 \geq h \geq 17$	$35 > h \geq 23$	$h \geq 35$	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Table 2.4 Current distortion limits for general subtransmission systems (69 001 V through 161 000 V).

I_{sc}/I_L	<11	$17 \geq h \geq 11$	$23 \geq h \geq 17$	$35 > h \geq 23$	$h \geq 35$	TDD
<20*	2.0	1.0	0.75	0.3	0.15	2.5
20<50	3.5	1.75	1.25	0.5	0.25	4.0
50<100	5.0	2.25	2.0	0.75	0.35	6.0
100<1000	6.0	2.75	2.5	1.0	0.5	7.5
>1000	7.5	3.5	3.0	1.25	0.7	10.0

For Table 2.3 and 2.4 following points should be noted:

*All power generation equipment is limited to those values of current distortion regardless of actual I_{sc}/I_L

Note:

- Maximum harmonic current distortion in percent of I_L
- Individual harmonic order (odd harmonics)
- Even harmonics are limited 25 % of the below listed values
- Current distortion that results in DC offset are not allowed
- I_{sc} = maximum short circuit current at PCC
- I_L = maximum demand load current (fundamental frequency component) at PCC

Table 2.5 Current distortion limits for general transmission systems (<161 kV), distributed generation and cogeneration.

I_{sc}/I_L	<11	17≥h≥11	23≥h≥17	35 > h≥ 23	h≥35	THD
<50	2.0	1.0	0.75	0.3	0.15	2.5
≥50	3.0	1.5	1.15	0.45	0.22	3.75

*All power generation equipment is limited to those values of current distortion regardless of actual I_{sc}/I_L

Note: Maximum harmonic current distortion in percent of I_L

Individual harmonic order (odd harmonics)

Even harmonics are limited 25% of the below listed values

Current distortion that results in DC offset are not allowed

I_{sc} = maximum short circuit current at PCC

I_L = maximum demand load current (fundamental frequency component) at PCC.

2.1.1.2 Guidelines for the Utilities

Recommended voltage distortion limits are expressed in THD. THD is total (RSS) harmonic voltage in the presence of nominal fundamental frequency voltages. The limits for utilities are given in Table 2.6. The limits listed below should be used as design values for "worst case" of the normal operation. For shorter periods (during start ups or unusual conditions the limits may be exceeded by 50 %.

Table 2.6 Voltage distortion limits.

Bus Voltage at PCC	Individual Voltage Distortion(%)	Total Voltage Distortion THD (%)
69 kV and below	3.0	5.0
69.001kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

2.1.2.IEC Limits

International Electrotechnical Commission (IEC) limits [11-13] for harmonics are discussed in this section.

2.1.2.1 Current Distortion Limits

IEC 61000-3-2 which describes Limits for harmonic current emissions (equipment output current less than or equal to 16A per phase are given in Table 2.7

Table 2.7 IEC Current distortion limits.

h	3	5	7	9	11	13	15	From 15 to 39
Max. I_h A	2.3	1.14	0.77	0.4	0.33	0.21	0.15	$0.15/h$

2.1.2.2 Voltage Distortion Limits

Limits of allowable voltage distortion set by IEC 61000-2-4 and IEC 61000-2-2 are provided in Tables 2.8 to 2.10. Class 2 applies to PCC's (point of common coupling) and IPC's (in-plant point of coupling) in industrial environments in general while class 3 applies only to IPC's in industrial environments.

As per this standard THD_V should be less than 8 % for class 2 while it should be less than 10 % for class 3.

Table 2.8 IEC 61000-2-2 voltage harmonic distortion limits in public low voltage networks.

Odd harmonics		Even harmonics		Triplen harmonics	
h	% V_h	h	% V_h	h	% V_h
5	6	2	2	3	5
7	5	4	1	9	1.5
11	3.5	6	0.5	15	0.3
13	3	8	0.5	≥21	0.2
17	2	10	0.5		
19	1.5	≥ 12	0.2		
23	1.5				
25	1.5				
≥ 29	x				

THD less than 8 % for all harmonics up to 40.

$x = 0.2 + 12.5/h$

Table 2.9 IEC 61000-2-4 voltage harmonic distortion limits in public industrial plants Class 2.

Odd harmonics		Even harmonics		Triplen harmonics	
h	% V_h	h	% V_h	h	% V_h
5	6	2	2	3	5
7	5	4	1	9	1.5
11	3.5	6	0.5	15	0.3
13	3	8	0.5	≥ 21	0.2
17	2	10	0.5		
19	1.5	≥ 12	0.2		
23	1.5				
25	1.5				
≥ 29	x				

$x = 0.2 + 12.5/h$

Table 2.10 IEC 61000-2-4 voltage harmonic distortion limits in public industrial plants Class 3.

Odd harmonics		Even harmonics		Triplen harmonics	
h	% Vh	h	% Vh	h	% Vh
5	8	2	3	3	6
7	7	4	1.5	9	2.5
11	5	≥ 6	1	15	2
13	4.5			21	1.75
17	4			≥ 27	1
19					
23	3.5				
25	3.5				
≥ 29	y				

where $y = 5\sqrt{\frac{11}{h}}$

2.2 PASSIVE FILTERS

The shunt filter is said to be tuned some frequency which makes its inductive and capacitive reactances equal. The quality factor Q determines the sharpness of the tuning. Typical value for high Q is 50 to 60 and low Q is between 0.5 – 5. Quality

factor of the tuned passive filter is defined as the ratio of the reactance at resonance to resistance.

$$Q = \frac{X_o}{R} \tag{2.1}$$

The extent of filter detuning from the nominal tuned frequency is represented by factor δ. This factor includes various effects e.g. variations in the supply frequency, variations in the filter capacitance and inductance caused by aging and temperature, initial off-tuning caused by manufacturing tolerances and finite size of tuning steps.

The overall detuning in per unit of the nominal tuned frequency, is

$$\delta = (\omega - \omega_n) / \omega_n \tag{2.2}$$

Moreover, a change of L or C of say 2 % causes the same detuning as a change of system frequency of 1 %. Therefore δ is often expressed as

$$\delta = \frac{\Delta f}{f_n} + \frac{1}{2}\left(\frac{\Delta L}{L_n} + \frac{\Delta C}{C_n}\right) \tag{2.3}$$

The size of a filter is defined as the reactive power that the filter supplies at fundamental frequency. It is substantially equal to the fundamental reactive power supplied by the capacitors.

2.2.1 Design of Passive Filters

The ideal criterion for the design of filter is elimination of all harmonics completely. However, this ideal criterion is unrealistic both for technical and economical reasons as it is very difficult to estimate source harmonic generation, system impedance variations.

The design of the passive filter involves following steps

1. The harmonic current spectrum produced by the non-linear load is injected into circuit consisting of filters in parallel with the ac system and harmonic voltages are calculated.
2. The results of 1 are used to determine the specified parameters like voltage THD

3. The stresses in the filter components, i.e. capacitors, inductors and resistors are then calculated and with them their ratings and losses.

2.2.1.1 Tuned filters

A single tuned filter is a series RLC circuit tuned to the frequency of one harmonic. Its impedance is given by

$$Z_1 = R + j\left(\omega L - \frac{1}{\omega C}\right) \tag{2.4}$$

This at resonant frequency reduces to R. Fig. 2.1 shows the tuned filter.

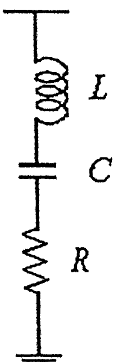

Fig. 2.1 Tuned Filter

Prior to design quality factor Q and the frequency variation factor δ are defined. Following relationships express filter impedance in terms of Q and δ

$$\omega = \omega_n(1 + \delta) \tag{2.5}$$

where $\omega_n = \frac{1}{\sqrt{LC}}$

Reactance at tuning frequency $X_o = \omega_n L = \frac{1}{\omega_n C} = \sqrt{\frac{L}{C}}$ *and* $Q = \frac{X_o}{R}$

$$C = \frac{1}{\omega_n X_o} = \frac{1}{\omega_n RQ} \quad and \quad L = \frac{X_o}{\omega_n} = \frac{RQ}{\omega_n} \tag{2.6}$$

Filter impedance at tuned frequency is given by Z_f

$$Z_f = R\left(1 + jQ\delta\left(\frac{2+\delta}{1+\delta}\right)\right) \tag{2.7}$$

2.2.1.2 Damped filters

The damped filters provide harmonic filtering for a wide spectrum. Fig. 2.2 shows the damped filter configuration.

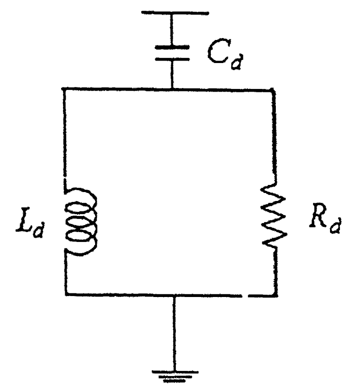

Fig. 2.2 Damped Filter.

The damped filter offers several advantages:

1. Its performance and loading is less sensitive to temperature variation, frequency deviation, component-manufacturing tolerances, etc.
2. It provides low impedance for wide spectrum of harmonics without the need for subdivision of parallel branches with increased switching and maintenance problems.
3. The use of tuned filters often results in parallel resonance between the filter and the system admittance at a harmonic order below the lower tuned filter frequency, or in between tuned filter frequencies. In such cases the use of one or more damped filters is a more acceptable alternative.

The main disadvantages of the damped filters are as follows

1. To achieve a similar level of filtering performance the damped filter needs to be designed for higher fundamental VA ratings, though in most cases a good performance can be met within the limits required for power factor correction.
2. The losses in the resistor and the reactor are generally higher.

Design of damped filter: When designing a damped filter the Q is chosen to give the best characteristic over the required frequency band. The behavior of damped filters has been described by following two parameters,

$$f_0 = \frac{1}{2\pi C_d R_d} \qquad\qquad m = \frac{L_d}{R_d * R_d * C_d} \tag{2.8}$$

Typical values of m are between 0.5 and 2. For a given capacitance these parameters are chosen to achieve an appropriately high admittance over the required range of frequency. For second order damped filter admittance is

$$G_f = \frac{m^2x^4}{R_1\left[\left(1-mx^2\right)^2 + m^2x^2\right]} \qquad B_f = \frac{x}{R_1}\left[\frac{1-mx^2+m^2x^2}{\left(1-mx^2\right)^2+m^2x^2}\right] \tag{2.9}$$

where $x = f/f_o$

Damped filters are classified as first order, second order, third order and C-type filters. First order filter is normally not used, as it requires large capacitor and fundamental frequency losses are very high. Second order filter provides the best filtering performance but has higher losses compared to third ordered filter. Third order filter has reduced losses but needs an extra capacitor. The performance of C-Type filter lies between that of second order and third order filter. This filter is more susceptible to fundamental frequency deviations and component value drift.

2.2.2 Passive Filter Component Properties

To prevent damage to the reactor and capacitor their ratings must be based on the most severe conditions expected (highest fundamental voltage, current, harmonic stresses, frequency deviation, harmonic resonances).

Capacitor: important parameters of capacitor for filtering applications are i) temperature coefficient (should be minimum to avoid detuning) ii) reactive power per unit volume iii) power loss iv) reliability and v) cost.

Inductors: skin effect and hysteresis losses should be calculated taking into consideration harmonic effect. Also detuing may be caused due to magnetic non-linearity. The Q factor affects the inductor design. Inductor ratings mainly depend on the maximum rms current and on the insulation level required to withstand switching surges.

2.3 ACTIVE FILTERS

Great deal of research has been made in the field of active power in last more than two decades [5-7]. This technology has been successfully implemented for harmonic reduction, reactive power compensation and voltage balance in ac power networks. All active power filters are developed with PWM converters (current source or voltage source inverters). The current fed PWM inverter bridge structure behaves as a non-sinusoidal current source to meet the harmonic current requirements of the non-linear load. It has self-supported dc reactor that ensures the continuos circulation of the dc current. They present good reliability, but have higher losses and require higher values of parallel ac capacitor filters to remove unwanted current harmonics. Moreover they can not be used in multilevel or multistep configurations to allow compensation in higher power ratings. The other converter used in active filter topologies is the voltage source PWM inverter. This converter is more suitable for active power filtering applications since it is lighter cheaper and expandable to multistep or multilevel versions. These versions improve its performance for high power rating compensation with lower switching frequencies. The PWM voltage source inverter has to be connected to ac mains through coupling reactors. An electrolytic capacitor keeps the dc voltage constant and ripple free.

Active filters can be further classified as series active filter, shunt active filter or unified active power quality conditioner based on its power circuit configuration.

- In the shunt active filter the active filter is in parallel with source and load. Active filter can be controlled to provide active filtering, reactive power compensation, current unbalance.
- Series filter comes in series with the source. It can be controlled to provide voltage harmonic filtering, voltage flicker, voltage unbalance, voltage notching. Basic purpose of this filter is to isolate load from the source.
- Unified power quality conditioner or universal active filter is combination of active series and active shunt filters. The dc link storage element (either inductor or dc-

bus capacitor) is shared between two current source or voltage source bridges operating as active series and active shunt compensator. This configuration is believed to be an ideal active filter, which eliminates both voltage and current harmonics and is capable of giving clean power to critical equipment.

Active filters can be further classified based on the control strategy to obtain the compensation commands. It is done either in frequency domain or time domain.
Control strategy in frequency domain is based on the Fourier analysis of distorted voltage and current signals to extract compensating commands. The device switching frequency is normally kept more than twice the highest compensating harmonic frequency. The online application of Fourier transform is a computationally cumbersome and time-consuming process.

Control methods of the active filters in time domain are on instantaneous derivation of compensating commands in the form of voltage or current signals from distorted and harmonic polluted environment. Majority of the active filters uses these methods for their operation. Some of the examples of time domain extraction methods are FBD method, instantaneous reactive power method, synchronous reference frame method, and symmetrical component method.

2.3.1 Extraction Methods for Reference Generation

In active filter control various components of the currents and voltages are extracted. These components are determined by the objective of compensation (whether it is for reactive power and/or harmonics and/or unbalance). Inverter is switched such that source current fulfils objective of compensation. In following paragraphs some methods used for reference generation are discussed.

2.3.1.1 FBD Method

Fryze in 1932 proposed new power definition in time domain [14]. According to this, if $v(t)$ is the source voltage and V is its RMS value, then the source current i can be decomposed in the time domain into an active current i_a and non-active current i_q, which are defined as

$$i_a(t) = \frac{P}{V^2} * v(t) \tag{2.10}$$

$$i_q(t) = i(t) - \frac{P}{V^2} * v(t) \tag{2.11}$$

where, $P = \frac{1}{T}\int_0^T (v * i)dt$ and $V = \sqrt{\frac{1}{T}\int_0^T v^2 dt}$

The active current component i_a has the same waveform and phase as the source voltage v. The average power transfer from source to load is associated only with active power current component i_a while the non-active component i_q increases the RMS value of the source current and causes an increase in undesired losses and voltage distortion. The non-active current i_q can be used as reference signal for the control of the active filters. It is to be noted from the equation (2.11) that a full period of voltage has to elapse to calculate the new value of current i_q.

Depenbrock [14] decomposed the reactive current i_q further into two current components, namely reactive component i_r and the distortion component i_d such that:

$$i_q = i_r + i_d \tag{2.12}$$

The reactive current component i_r has the same waveform and phase as that of the current in an inductor or capacitor with the same voltage across it. This current does not contribute to the energy flow and only increase the system losses and makes voltage regulation poor. The distortion component or the harmonic component i_d is the component, which remains out of the total current i after the active component i_a and the reactive component i_r have been extracted. The current component i_d is mainly responsible for voltage distortion in power system and EMI & RFI related problems.

All three components are mutually orthogonal and they are related to source current as per the following expression:

$$I^2 = I_a^2 + I_r^2 + I_d^2 \tag{2.13}$$

Where I_a, I_r, I_d are the RMS values of active, reactive and harmonic current components respectively. The instantaneous current components i_r, i_d, can be individually used as reference signal to achieve compensation objectives such as reactive power compensation, harmonic filtering etc. Further this decomposition

method can be applied to three-phase system as well as for system consisting m number of conductors. However, the calculation of i_r and i_d under asymmetrical conditions is quite involved due to use of complicated definition of reactive power.

Due to lack of simplicity and computational inefficiency these methods did not gain popularity for active filtering.

2.3.1.2 Instantaneous Reactive Power Theory

Three phase quantities are transformed into α-β orthogonal coordinates using following transformation [15].

$$\begin{bmatrix} e_0 \\ e_\alpha \\ e_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{2.14}$$

Conventional instantaneous power in three phase given by

$$p = e_a \,.\, i_a + e_b \,.\, i_b + e_c \,.\, i_c = e_\alpha \, i_\alpha + e_\beta \,.\, i_\beta \tag{2.15}$$

Instantaneous reactive power is defined as

$$q = e_\alpha \times i_\beta + e_\beta \times i_\alpha$$

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{2.16}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p \\ q \end{bmatrix} \tag{2.17}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p \\ 0 \end{bmatrix} + \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ q \end{bmatrix} = \begin{bmatrix} i_{\alpha p} \\ i_{\beta p} \end{bmatrix} + \begin{bmatrix} i_{\alpha q} \\ i_{\beta q} \end{bmatrix} \tag{2.18}$$

where, α- axis instantaneous active current: $i_{\alpha p} = \dfrac{e_\alpha}{e_\alpha^2 + e_\beta^2} p$

α- axis instantaneous reactive current: $i_{\alpha q} = \dfrac{-e_\beta}{e_\alpha^2 + e_\beta^2} q$

β- axis instantaneous active current: $i_{\beta p} = \dfrac{e_\beta}{e_\alpha^2 + e_\beta^2} p$

β- axis instantaneous reactive current: $i_{\beta q} = \frac{e_\alpha}{e_\alpha^2 + e_\beta^2} q$

For a power electronic converter (say cycloconverter) assuming that there are neither energy storage components nor losses the instantaneous real power input is equal to the instantaneous real power output. But instantaneous imaginary power input is not equal to the instantaneous imaginary power output. It is to be noted that both instantaneous real power and instantaneous imaginary power in a balanced sinusoidal three-phase circuit become constant. Instantaneous imaginary power is quite different in definition and physical meaning from conventional reactive power based on the average value concept.

The active power conditioner based on this theory eliminates the instantaneous reactive powers on the source side, which are caused by the instantaneous reactive power on load side. Further dc component of $i_{\alpha p}$ and $i_{\beta p}$ corresponds to conventional fundamental active current, its ac component represents instantaneous value of the harmonic currents.

2.3.1.3 Synchronous Reference Frame (SRF) Method

Using the d-q transformation three phase quantities are transformed into rotating reference frame. To achieve this the source current and line voltages of three-phase system are measured. From these values processor calculates the harmonic content of the source currents. Three phase currents i_{sa}, i_{sb}, i_{sc} are transformed into synchronous rotating frame using following transformation

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \mathrm{T}\,(\theta). \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \tag{2.19}$$

where $$T(\theta) = \frac{2}{3} \cdot \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \tag{2.20}$$

In the above equation θ represents the actual phase angle of line voltage space vector. i_d and i_q are the components of the resulting source current space vector in the fundamental mains frequency rotating coordinate system. The DC components of i_d and i_q represent positive sequence fundamental component of the source currents in three phase system. The remaining component of i_d and i_q represent the harmonic content in the current. This method can also be used for extracting individual harmonic content. If frame is rotated at that harmonic frequency that harmonic will become DC quantity which can be filtered to get the individual harmonic content [16]. From d-q frame a-b-c quantities can be obtained using following inverse transformation.

$$T^{1}(\theta) = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \tag{2.21}$$

2.3.1.4 Instantaneous Symmetrical Components Method

This generalized method can be applied to either 3-phase 3-wire or 3-phase 4-wire systems. This method gives freedom of choosing power factor as per one's desire, compared to other methods, which force it to unity [19.20]. Following paragraphs discuss its application to star connected load. Same theory can extended to delta connected loads.

Referring to Fig. 2.3 for balanced three phase supply

$$i_{sa} + i_{sb} + i_{sc} = 0 \tag{2.22}$$

Let us assume that the source voltages are balanced and are given by

$$v_{sa} = \sin\omega t, \quad v_{sb} = \sin(\omega t - 120°), \quad v_{sc} = \sin(\omega t + 120°) \tag{2.23}$$

From the definition of symmetrical components [20]

$$v_{sa1} = \frac{1}{\sqrt{3}}\left[v_{sa} + a v_{sb} + a^2 v_{sc}\right] \quad \text{where} \qquad a = e^{j120°} \tag{2.24}$$

It can be shown that phase angle of this vector is given by

$$\phi = \angle(v_{sa1}) = \tan^{-1}\left\{\frac{\frac{\sqrt{3}}{2}v_{sb} - \frac{\sqrt{3}}{2}v_{sc}}{v_{sa} - \frac{1}{2}v_{sb} - \frac{1}{2}v_{sc}}\right\} = \tan^{-1}\left\{\frac{\frac{\sqrt{3}}{2}\left(v_{sb} - v_{sc}\right)}{\frac{3}{2}v_{sa}}\right\} \tag{2.25}$$

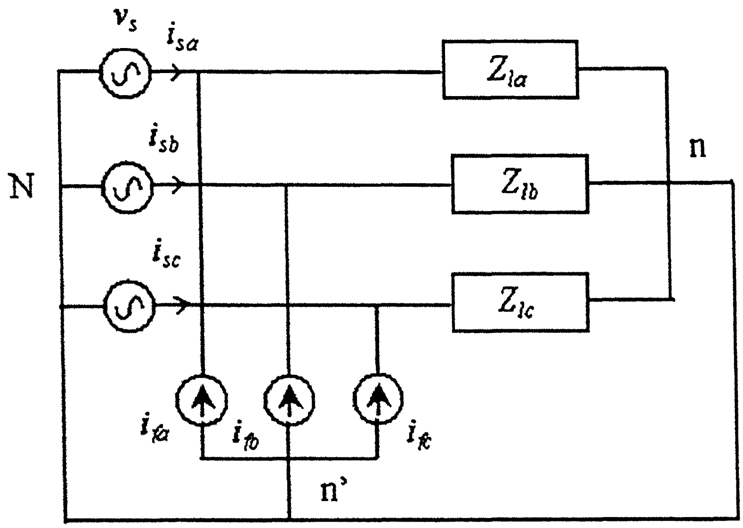

Fig. 2.3 3-phase,4-wire distribution system with star connected load

Substituting the instantaneous values in above equation we get

$$\phi = \tan^{-1}\left\{\frac{-\cos\omega t}{\sin\omega t}\right\} = \omega t - \frac{\pi}{2} \tag{2.26}$$

angle of v_{sa1} varies linearly with t. This will allow us to force current vector at any desired angle with respect to the voltage vector. Assuming phase of vector i_{sa1} lags that of vector v_{sa1} by an angle ϕ,

$$\angle\{v_{sa} + av_{sb} + a^2v_{sc}\} = \angle\ \{i_{sa} + ai_{sb} + a^2i_{sc}\} + \phi \tag{2.27}$$

Substituting the values of a and a^2

$$\angle\left\{\left(v_{sa} - \frac{1}{2}v_{sb} - \frac{1}{2}v_{sc}\right) + j\frac{\sqrt{3}}{2}\left(v_{sb} - v_{sc}\right)\right\} = \angle\left\{\left(i_{sa} - \frac{1}{2}i_{sb} - \frac{1}{2}i_{sc}\right) + j\frac{\sqrt{3}}{2}\left(i_{sb} - i_{sc}\right)\right\} + \phi$$

(2.28)

Equating the angles we can write from the above equation

$$\tan^{-1}(K_1 / K_2) = \tan^{-1}(K_3 / K_4) + \phi \tag{2.29}$$

where $K_1 = \frac{\sqrt{3}}{2}(v_{sb} - v_{sc}), K_2 = v_{sa} - \frac{1}{2}v_{sb} - \frac{1}{2}v_{sc}$,

$K_3 = \frac{\sqrt{3}}{2}(i_{sb} - i_{sc}), K_4 = i_{sa} - \frac{1}{2}i_{sb} - \frac{1}{2}i_{sc}$

Using the formula, $tan\,(\alpha + \beta) = \frac{tan\,\alpha + tan\,\beta}{1 - tan\,\alpha\, tan\,\beta}$

Equation (2.29) can be expanded as

$$\frac{K_1}{K_2} = tan\left[tan^{-1}(K_3 / K_4) + \phi\right] = \frac{K_3 / K_4 + tan\,\phi}{1 - (K_3 / K_4)\,tan\,\phi} \tag{2.30}$$

Solving the above equation we get

$$(v_{sb} - v_{sc} - 3\beta v_{sa})i_{sa} + (v_{sc} - v_{sa} - 3\beta v_{sb})i_{sb} + (v_{sa} - v_{sb} - 3\beta v_{sc})i_{sc} = 0 \tag{2.31}$$

where $\beta \equiv tan\,\phi / \sqrt{3}$

Following points should be noted:

1. When the power factor angle is assumed to be zero, (2.31) implies that the instantaneous reactive power supplied by the source is zero. When this angle is not zero, the source supplies reactive power that is equal to β times instantaneous power.
2. Instantaneous power in balanced sinusoidal system is constant
3. In unbalanced circuit it has double frequency component
4. In presence of harmonics oscillating component is added to the power.

For source to supply only average value of load power compensator should supply the oscillating component.

We should obtain

$$v_{sa}i_{sa} + v_{sb}i_{sb} + v_{sc}i_{sc} = p_{lav} \tag{2.32}$$

Where p_{lav} is the average power drawn by the load. Since the harmonic component in the load does not require any real power. the source only supplies the fundamental active power required by the load.

$$\begin{bmatrix} 1 & 1 & 1 \\ v_{sb}-v_{sc}-3\beta v_{sa} & v_{sc}-v_{sa}-3\beta v_{sb} & v_{sa}-v_{sb}-3\beta v_{sc} \\ v_{sa} & v_{sb} & v_{sc} \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ plav \end{bmatrix} \quad (2.33)$$

$$i^*_{fk} = i_{lk} - i_{sk},\ k = a,\ b,\ c$$

$$\begin{aligned} i^*_{fa} &= i_{la} - \frac{v_{sa}+(v_{sb}-v_{sc})\beta}{v_{sa}^2+v_{sb}^2+v_{sc}^2}\, p_{lav} \\ i^*_{fb} &= i_{lb} - \frac{v_{sb}+(v_{sc}-v_{sa})\beta}{v_{sa}^2+v_{sb}^2+v_{sc}^2}\, p_{lav} \\ i^*_{fc} &= i_{lc} - \frac{v_{sc}+(v_{sa}-v_{sb})\beta}{v_{sa}^2+v_{sb}^2+v_{sc}^2}\, p_{lav} \end{aligned} \quad (2.34)$$

Similar analysis can be carried out for delta connected load and for unbalanced source.

2.4 ACTIVE HYBRID FILTERS

Pure active filters are costly and less efficient while pure passive filters require great deal of engineering for effectiveness. Hybrid active filters attempt to overcome limitations of pure passive and pure active harmonic filters. Hybrid filters are broadly classified as hybrid filter with series active conditioner and hybrid filter with shunt active conditioner.

Different topologies of Hybrid Filters are discussed below.

2.4.1 Active filter in series with the load and supply

The shunt passive filter provides the filtering of the harmonics generated by the load whereas active series filter acts as a harmonic isolator between load and the source [23]. When active filter is not connected the passive filter compensates load harmonic current. Filtering characteristic will depend upon the ratio of source side impedance and the passive filter impedance at the given harmonic. If source impedance is very small or the passive filter is not sharply tuned to the harmonic frequencies generated by the load, desirable filtering characteristic would not be obtained. Also harmonic resonance phenomenon may take place at harmonic frequency at which source and

filter impedance become equal. If this happens much large amount of harmonic currents would flow in the source.

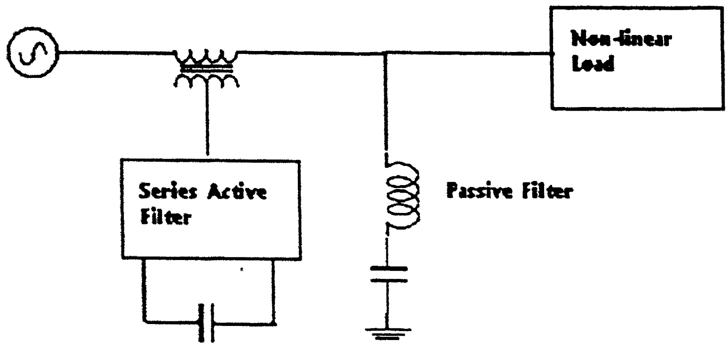

Fig. 2.4 Shunt passive series active hybrid filter

When active filter is connected and is controlled as a voltage source, the active filter forces all the harmonics contained in the load current to flow in the passive filter so that no harmonic current flows in the source. No fundamental voltage is applied to the active filter, which results in great reduction in the rating of the active filter.

2.4.2 Active filter in parallel with load source and passive filter

In this topology both the active and the passive filters are connected in parallel with the load [24,26]. The function of the active filter is to compensate harmonic currents after the passive filters. This topology leads to retrofit applications with the existing passive filters.

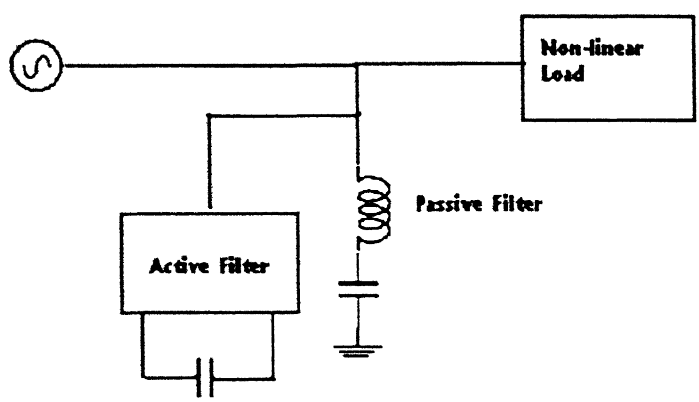

Fig. 2.5 Shunt passive shunt active hybrid filter.

The passive filter is designed to provide its intended compensating harmonic currents. The active filter provides infinite impedance to fundamental and very low resistance for the harmonic frequencies.

2.4.3 Active filter in series with the passive filter

It consists of a small rated active filter in series with the passive filter as shown in the figure[16,17,25]. This topology is suitable for harmonic compensation as opposed to the harmonic isolation of large non-linear multiple and diverse loads. Power factor correction capacitor can also be used as a cost-effective passive filter with a PWM VSI based active filter. Further "active inductance" of inverter or leakage inductance of the coupling transformer with the power factor correction capacitor can be used to provide tuning at the dominant harmonic frequency. The active filter controlled by a SRF based controller provides tuning for the existing mistuned passive filter due to L-C component tolerances, thus improving filtering characteristic of the passive filter. It can also be provided with current limiting feature under ambient harmonic loads and supply voltage distortion. This scheme is described in this thesis.

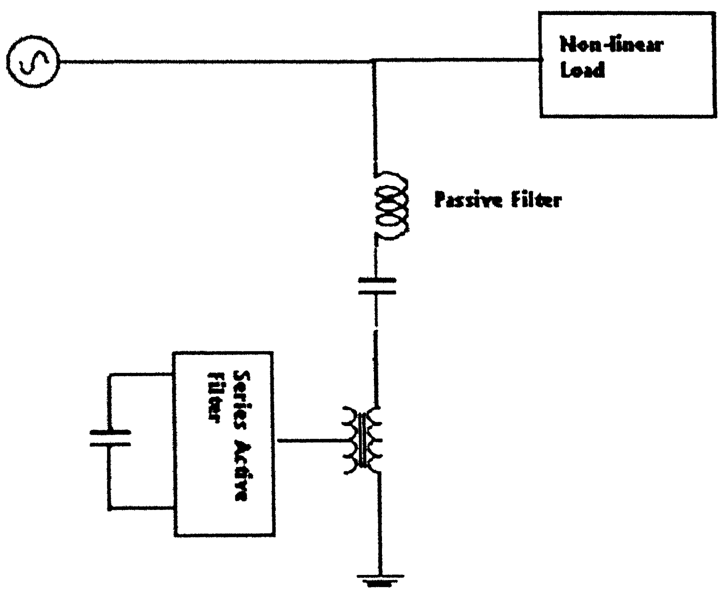

Fig. 2.6 Hybrid filter with shunt passive and active filter in series with passive filter.

Advantages of this configuration are

- It requires very small rated active filter.
- This topology is amenable for retrofit applications with existing passive filters.
- It can be made to operate without any energy storing device (battery).
- This topology is most suitable for the high power applications.
- Using Synchronous Reference Frame based controller for dominant harmonic switching inverter switching frequency can be made considerably low.
- It is relatively easier to protect and does not require expensive switchgear compared to series active hybrid filter.

CHAPTER 3

ACTIVE HYBRID FILTER

INTRODUCTION

An active filter, which consists of a dominant harmonic switching inverter supported by DC capacitor, is connected in series with the L-C passive filter. The passive filter capacitor supports the fundamental line voltage and thus enables the small rating requirement of the active filter, which provides harmonic voltage output. Synchronous Reference Frame (SRF) based controller is used in this thesis to implement the dynamically varying either negative or positive "active inductance" [28]. The desired active "active inductor" inverter reference voltage is calculated and synthesized by three-phase PWM voltage source inverter.

Dominant harmonics in the power system normally are 5^{th}, 7^{th}, 11^{th} and 13^{th}. Higher order harmonics are significantly reduced by series inductive impedance of the system. Fig. 3.1 shows the power circuit diagram of the hybrid filter simulated and analyzed in this thesis. It has two passive filter branches, one for 5^{th} and the other for 7^{th} order harmonic. Active filters of that harmonic are connected in series with L-C of the passive filter. If required, high pass filter may also be used.

3.1 ANALYSIS OF THE EQUIVALENT CIRCUIT

The single-phase equivalent circuit of this scheme is drawn in Fig. 3.2. In this equivalent circuit load is modeled as current source. This current source will include the harmonic currents of the load. Series active filter is modeled as voltage source. This voltage source will contain the dominant harmonic component at which the inverter is

switching, fundamental component and sideband harmonic voltage components.

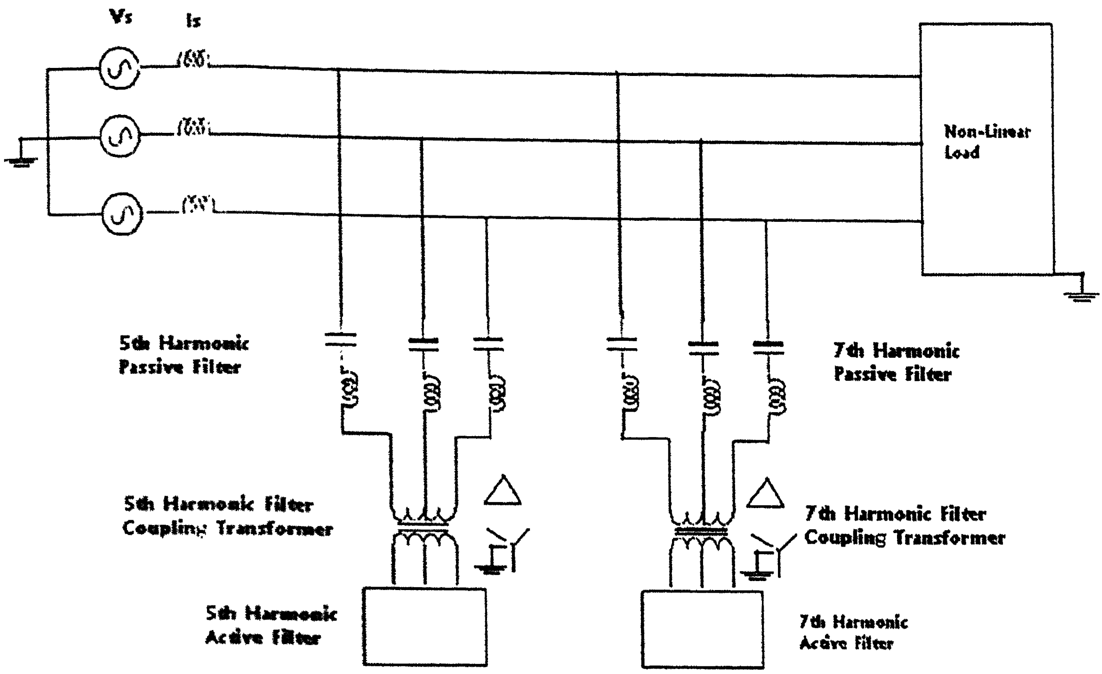

Fig.3.1 Schematic diagram of the hybrid active filter.

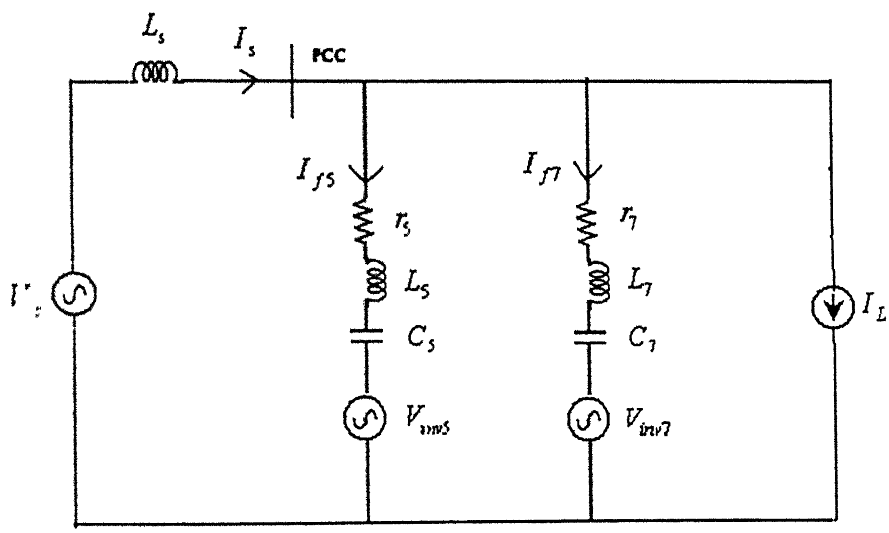

Fig. 3.2 Single-phase equivalent circuit

The three phase quantities are transformed into synchronously rotating frame. Frequency of the rotation of the frame can be decided depending upon the need of the control. If frame is rotated at 50 Hz then fundamental current or voltage becomes DC value and negative sequence and harmonic quantity become AC quantities. Fundamental quantity, which is DC, can be extracted by low pass filter. Similarly to

extract the harmonic quantity, the frame is rotated at that harmonic speed so that it becomes DC and can be extracted by low pass filter. It should be noted that for negative sequence harmonics, the frame should be rotated at that harmonic frequency in negative direction. For example for extraction of 5th harmonic, which is negative sequence harmonic frame is rotated at -250 Hz. From d-q frame to a-b-c reference frame transformation can done using inverse SRF transformation matrix as explained in Chapter 2.

Now we obtain an expression for the inverter output voltage. In the following analysis it will be seen that the rating requirement of the active filter will be small. This will lead to fulfillment of our aim of achieving a cost-effective solution harmonic filtering. The circuit of Fig. 3.2 can be modeled in the 5th harmonic d-q frame as shown in Fig. 3.3.

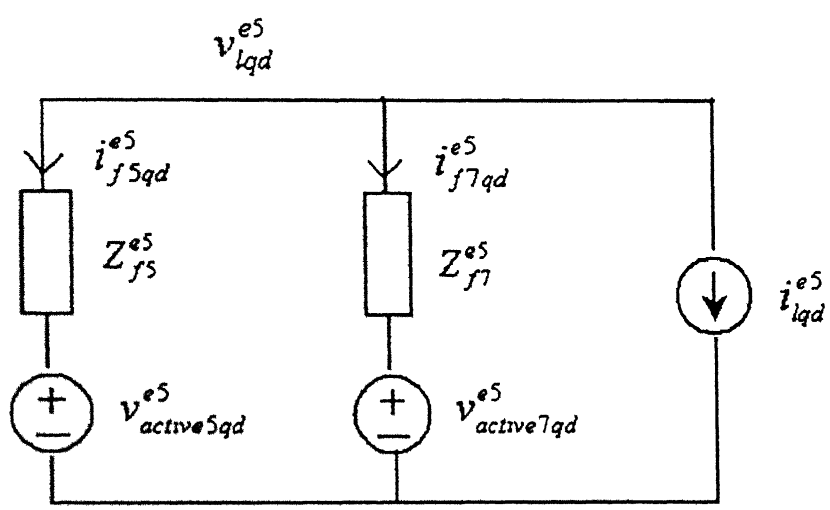

Fig.3.3. 5th harmonic equivalent circuit

Let us assume in this analysis that source is free from 5th harmonic distortion and active filter is performing ideally so that no 5th harmonic current is flowing in the source from load. This reduces the circuit of Fig. 3.2 to that shown in Fig. 3.3

$$i_{f5qd}^{e5} = \frac{v_{active7qd}^{e5}}{Z_{f5}^{e5} + Z_{f7}^{e5}} - \frac{v_{active5qd}^{e5}}{Z_{f5}^{e5} + Z_{f7}^{e5}} - \frac{Z_{f7}^{e5} \cdot i_{lqd}^{e5}}{Z_{f5}^{e5} + Z_{f7}^{e5}} \tag{3.1}$$

where, $\omega_5 = -5 \cdot \omega$; ω is the fundamental frequency and

$$Z_{f5}^{e5} = r_5 + j\omega_5 L_5 + \frac{1}{j\omega_5 C_5}$$

$$Z_{f7}^{e5} = r_7 + j\omega_5 L_7 + \frac{1}{j\omega_5 C_7}$$

$v_{active5qd}^{e5}$ = 5th harmonic voltage component of the fifth harmonic active filter

$v_{active7qd}^{e5}$ = 5th harmonic voltage component of the seventh harmonic active filter

v_{lqd}^{e5} = 5th harmonic voltage component of the load voltage

$$v_{active5qd}^{e5} = v_{lqd}^{e5} - i_{f5qd}^{e5} Z_{f5}^{e5} \tag{3.2}$$

Substituting (3.1) in (3.2)

$$v_{active5qd}^{e5} = v_{lqd}^{e5} - \left(\frac{v_{active7qd}^{e5}}{Z_{f5}^{e5} + Z_{f7}^{e5}} - \frac{v_{active5qd}^{e5}}{Z_{f5}^{e5} + Z_{f7}^{e5}} - \frac{Z_{f7}^{e5} \cdot i_{lqd}^{e5}}{Z_{f5}^{e5} + Z_{f7}^{e5}} \right) \cdot Z_{f5}^{e5} \tag{3.3}$$

Multiplying both sides by $Z_{f5}^{e5} + Z_{f7}^{e5}$ we get

$$\begin{aligned} v_{active5qd}^{e5} \cdot \left(Z_{f5}^{e5} + Z_{f7}^{e5}\right) = v_{lqd}^{e5} \cdot \left(Z_{f5}^{e5} + Z_{f7}^{e5}\right) - v_{active7qd}^{e5} \cdot Z_{f5}^{e5} \\ + v_{active5qd}^{e5} \cdot Z_{f5}^{e5} + Z_{f7}^{e5} \cdot i_{lqd}^{e5} \cdot Z_{f5}^{e5} \end{aligned} \tag{3.4}$$

Simplifying we get

$$v_{active5qd}^{e5} = v_{lqd}^{e5} \cdot \left(\frac{Z_{f5}^{e5} + Z_{f7}^{e5}}{Z_{f7}^{e5}} \right) + Z_{f5}^{e5} \cdot i_{lqd}^{e5} - \left(\frac{Z_{f5}^{e5}}{Z_{f7}^{e5}} \right) \cdot v_{active7qd}^{e5} \tag{3.5}$$

Observing the above equation and taking into consideration the fact that Z_{f5}^{e5} at 5th harmonic frequency is considerably small, the rating of the active filter would be very small. Also fifth harmonic sideband voltage of seventh harmonic filter inverter will not have any significant effect on harmonic isolation at fifth harmonic by fifth harmonic active filter.

3.2 COMPUTATION OF THE DESIRED ACTIVE FILTER OUTPUT VOLTAGE

Three phase harmonic filter currents are measured and transferred into fifth harmonic SRF quantities. Then they are filtered through a low-pass to extract the 5th harmonic content in them. The process of SRF transformation and low pass filtering is applied to load terminal voltages V_{la}, V_{lb}, V_{lc}

The active impedance commands L_{active} and R_{active} are obtained from following equations [18].

$$L_{active5} = -\operatorname{Im}\left[\frac{v_{lq}^{e5} - j \cdot v_{ld}^{e5}}{i_{f5q}^{e5} - j \cdot i_{f5d}^{e5}}\right] \cdot \frac{1}{\omega_5} \quad \text{and} \quad R_{active5} = -\operatorname{Re}\left[\frac{v_{lq}^{e5} - j \cdot v_{ld}^{e5}}{i_{f5q}^{e5} - j \cdot i_{f5d}^{e5}}\right] \tag{3.6}$$

Reference voltage for 5th harmonic active filter inverter is obtained from following expressions

$$v_{active5q}^{e5} - j \cdot v_{active5d}^{e5} = \left(R_{active5} + j \cdot \omega_5 \cdot L_{active5}\right) \cdot \left(i_{f5q}^{e5} - i_{f5d}^{e5}\right) \tag{3.7}$$

Similarly for the seventh order harmonic active filter

$$L_{active7} = -\operatorname{Im}\left[\frac{v_{lq}^{e7} - j \cdot v_{ld}^{e7}}{i_{f7q}^{e7} - j \cdot i_{f7d}^{e7}}\right] \frac{1}{\omega_7} \quad \text{and} \quad R_{active7} = -\operatorname{Re}\left[\frac{v_{lq}^{e7} - j \cdot v_{ld}^{e7}}{i_{f7q}^{e7} - j \cdot i_{f7d}^{e7}}\right] \tag{3.8}$$

and reference voltage is equal to

$$v_{active7q}^{e7} - j \cdot v_{active7d}^{e7} = \left(R_{active7} + j \cdot \omega_7 \cdot L_{active7}\right) \cdot \left(i_{f7q}^{e7} - i_{f7d}^{e7}\right) \tag{3.9}$$

By injecting $v_{activeqd}$ the mistuning of the passive filter will be corrected. Consequently, the fifth harmonic component of the load current will be constrained in the fifth harmonic filter branch. It should be noted that as discussed in Section 3.2 the seventh harmonic active filter inverter will not interfere with the harmonic isolation at the fifth harmonic frequency and also will not result in an increased voltage rating of the fifth harmonic active filter inverter.

One important point should be noted that if supply system contains fifth harmonic distortion then this perfect tuning of the filter branch would act as a sink to the supply

harmonics. At any cost this must be avoided as it will not only cause large harmonic voltages but also will overload both active and passive filters and will result in frequent blowing of fuses and increase in losses. To avoid this there should be limiter, which will monitor the filter current. If this filter current is more than specified value DC bus voltage should not be allowed to change such that perfect removal of mistuning takes place. At the same time care should be taken to satisfy IEEE 519 at PCC [1].

3.3 INVERTER FOR ACTIVE HYBRID FILTER

Inverter used in active filter is shown in Fig.3.4 It is realized using IGBT's AC side inductance is realized using the inductance of the transformer. Details of the coupling transformer are discussed in Section 3.5.1.Firing scheme is discussed in Section 3.4.1

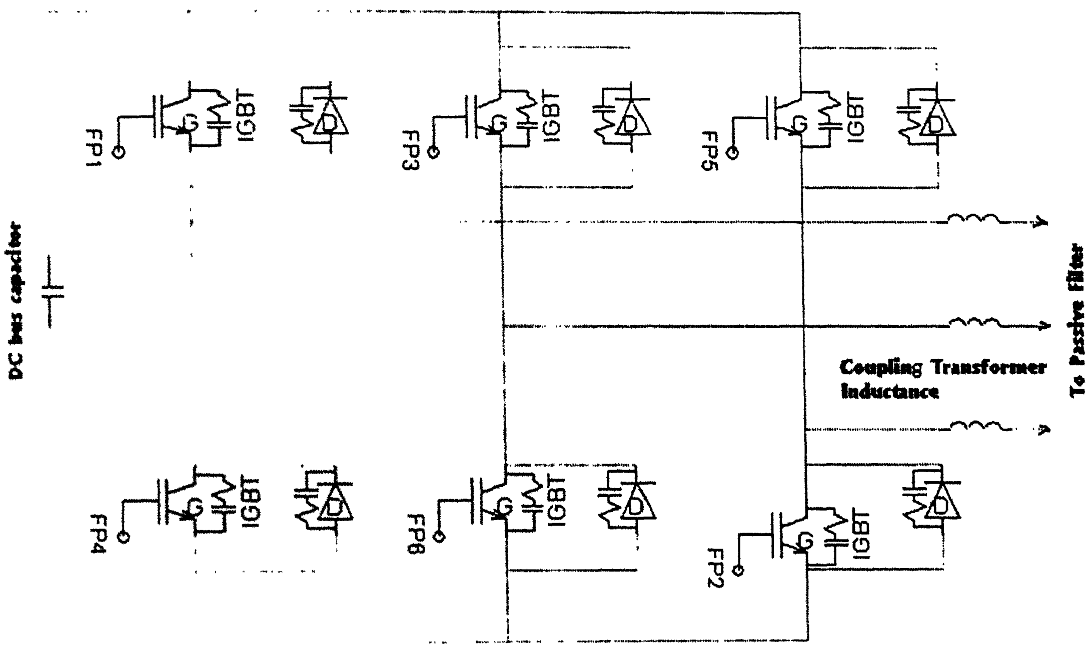

Fig.3.4 Inverter used for the active hybrid filter.

3.3.1 Control Strategy for the Active Hybrid Filter

Three phase filter currents and the voltage at PCC is measured and transformed into d-q reference frame rotating at –250 Hz frequency (350Hz for the 7^{th} order harmonic filter) The 5^{th} harmonic quantity is extracted by low pass filter as it is dc in this frame. Manipulating these quantities, commands for the active filter inverter are generated as

described in section 3.3. Fig. 3.5 shows a schematic block diagram of the control strategy for the hybrid active filter.

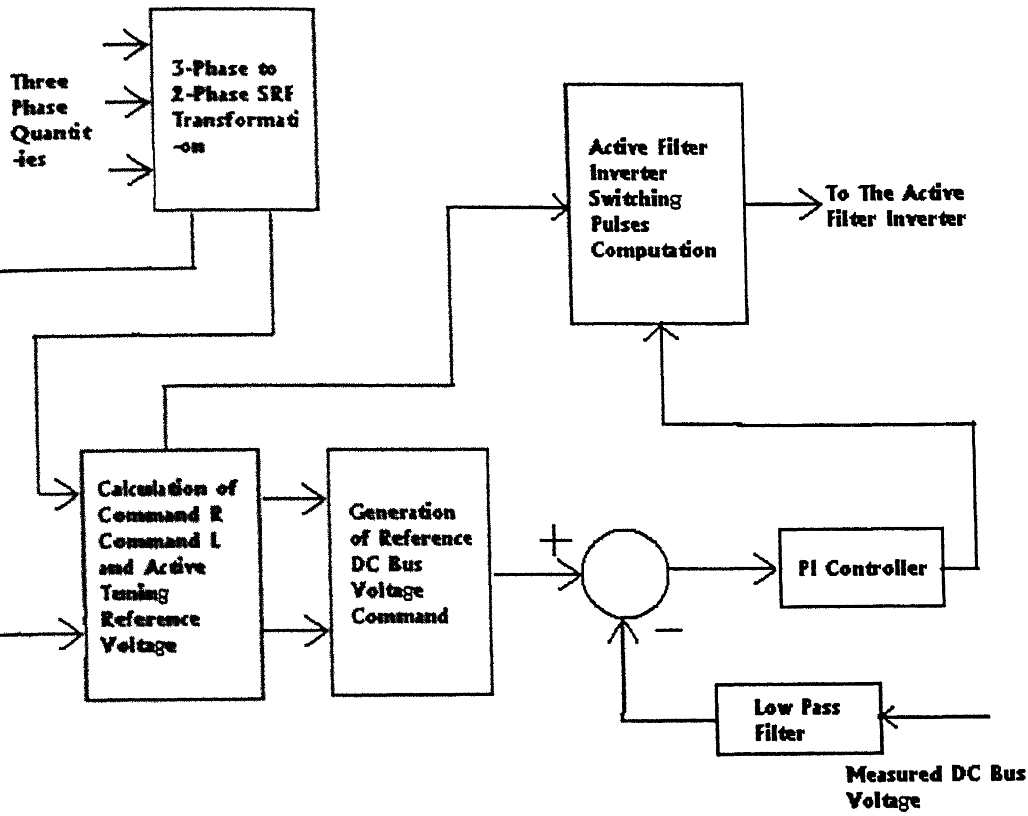

Fig.3.5 Block diagram of the controller of the scheme for hybrid active filter

This inverter is dominant harmonic switching inverter. Reduction in bandwidth of the inverter will simplify the inverter and reduce the cost. The inverter generates the two voltage components in a self-sufficient manner. The 5th harmonic ($v^{e5}_{active5qd}$) component to achieve the active tuning of 5th harmonic passive filter branch and fundamental component to control DC bus voltage and to balance the power flow of the active filter. This is achieved using modified sine-triangle PWM. For 5th harmonic active filter inverter, the triangular wave has a frequency of 250 Hz. Modulation-index, which is ratio of the amplitude of the reference sine wave and amplitude of the triangular wave is small. This makes the 5th harmonic content in the output high compared to the fundamental.

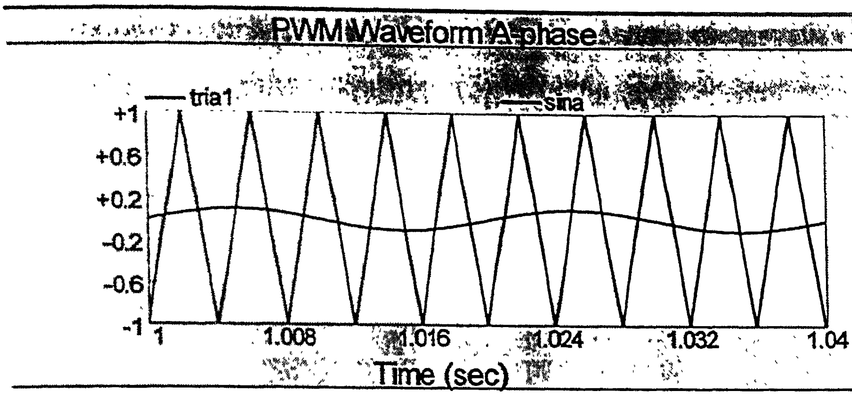

Fig. 3.6 (a) PWM A-Phase waveforms.

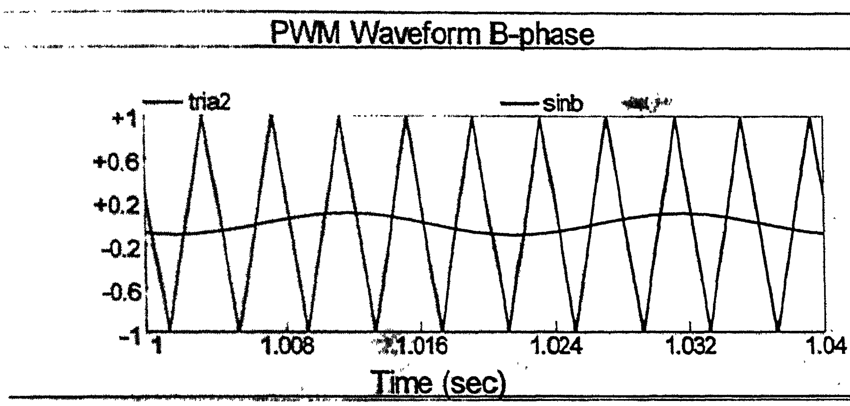

Fig. 3.6 (b) PWM B-phase waveforms.

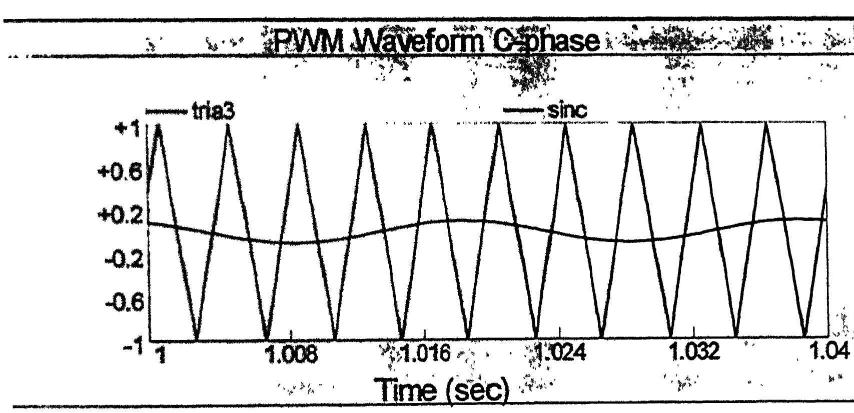

Fig. 3.6 (c) PWM C-phase waveforms.

Fig. 3.6 shows the waveforms of the PWM scheme. Harmonic contents are also given in the Table 3.1 and phase to neutral waveform of the inverter output voltage is shown in Fig. 3.7. In the output, the sideband of ($f_c \pm 2f_r$) would have dominant presence, where f_c is triangular carrier wave frequency and f_r is the reference sine wave frequency. In our case f_c = 250Hz and f_r = 50Hz. Side band of (250 – 100) = 150 will

not exist because of its zero sequence nature. And the sideband (250 + 100) is less than 1 % of the 250 Hz component. The triangular wave is synchronized with the active tuning command.

In inverter output voltage fundamental is present to compensate for the losses and to maintain DC bus voltage to desired value. The triangular wave is phase displaced by 120 degrees for each phase as shown in the Fig. 3.5.

Output waveform of the inverter

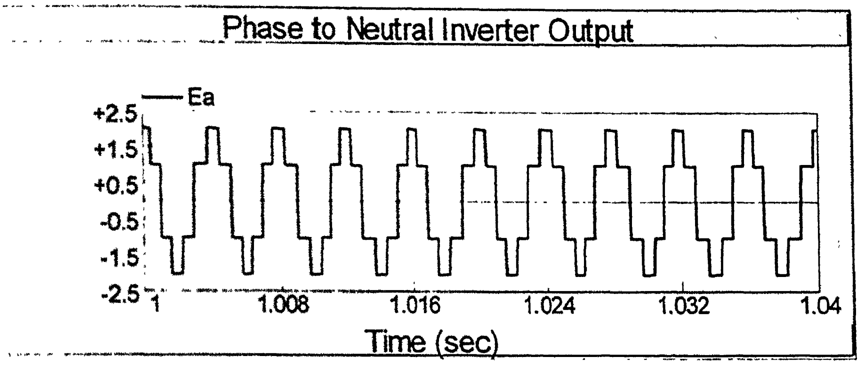

Fig. 3.7 Phase to neutral waveform of Inverter.

Table 3.1 Harmonic Contents of the Inverter Output Voltage shown in Fig. 3.6.

Harmonic Order	1st	5th	7th
Magnitude	0.315	1.94	0.014

The line-neutral output voltage contains the required voltage components at the fundamental frequency and also, at the harmonic frequency due to the use of three phase fundamental references and three-phase triangular carrier phase displaced by 120°. The magnitude and phase of the fundamental frequency references control the magnitude and phase of the fundamental component. The magnitude of the component at carrier frequency is (e.g. 5th) is proportional to the dc bus voltage. The phase of component at carrier frequency is controlled by the phase of the triangular carriers.

The injection of fundamental voltage has little effect on the reactive power compensation, because it is very small compared to the fundamental voltage across passive filter capacitor.

3.3.2 DC Bus Control

Inverter DC bus voltage reference for 5th harmonic hybrid filter is calculated from equation (3.10)

$$V_{dc}^{*} = K_{gain} \cdot \sqrt{(v_{active5q}^{e5})^2 + (v_{active5d}^{e5})^2} \tag{3.10}$$

The gain factor is used for normalization. Similar equation can be written for 7th harmonic hybrid filter. The DC capacitor control is done using PI controller. The desired DC bus voltage is calculated and compared with actual value. Before comparing the measured DC capacitor voltage is filtered to remove ripple. This avoids the possible harmonic interaction among active filter, utility and the nonlinear load. The error is fed to the PI controller. PI controller output controls the phase of sine wave. The required active power exchange is done at fundamental frequency, which is controlled by the amplitude and phase of the reference sine wave. This DC bus regulation and power balancing function of this controller eliminates the need for any energy storage device or additional power supply requirement in this system.

3.4 DESIGN CONSIDERATIONS FOR PASSIVE ELEMENTS OF ACTIVE HYBRID FILTER

In this scheme inverter output waveform contains dominant harmonics. this necessitates some modifications in the coupling transformer and passive filter design. These issues are briefly dealt in the following sections.

3.4.1 Coupling Transformer

Normally while studying power electronic interface to the power system, coupling transformer is not given its due consideration. Researchers in this field consider coupling transformer as an integral part of the active filter, which is controlled as a voltage source. In addition to providing inductive interface for the active filter, the coupling transformer can be used to optimize the size of the active filter. Proper study needs to be done to optimize the size of transformer vis-a-vis the active filter. This will lead to the most economic hybrid filter. Cost is a very important factor in harmonic

filtering, as harmonic filtering does not directly affect production level. Following paragraphs discuss the special design considerations of the coupling transformer used in this hybrid active filter. The secondary side current of the transformer depends upon the passive filter. For 5th harmonic passive filter branch the current flowing through the primary will be primarily fundamental and 5th harmonic current. Secondary side voltage at given harmonic of the transformer is equal to the product of the harmonic current flowing and the harmonic impedance of the passive filter at that frequency. Harmonic currents of other than tuned frequency are small in magnitude so they can be neglected for calculation purposes. The kVA rating of the transformer is calculated from (3.11)

$$kVA = \sqrt{\sum_{n=1}^{\infty} V_n^2} \cdot \sqrt{\sum_{n=1}^{\infty} I_n^2} \tag{3.11}$$

where, V_n = n[th] order harmonic voltage and

I_n = n[th] order harmonic current

Transformer should not be operated in saturation region to avoid additional distortion. Voltage contains the harmonic therefore magnetic flux of the transformer is comprised of that harmonic magnetic flux. For 5th harmonic filter coupling transformer

$$V_5 = 4.44 f_5\, N\, A\, B_{m5} \tag{3.12}$$

where, V_5 = 5th harmonic voltage

f_5 = 5th harmonic frequency

N = number of turns of primary winding

A = area of the core

B_{m5} = maximum 5th harmonic flux density in the core.

Maximum flux density of the transformer is

$$B_m = B_{m5} = \frac{V_5}{4.44 f_5 NA} = \frac{\dfrac{V_s}{5}}{4.44 f_0 NA} \tag{3.13}$$

Thus to make sure that transformer flux density does not exceed B_m it should be designed as equivalent fundamental frequency transformer with $V_1 = V_5 / 5$.

As frequency of voltage and current are higher than the line frequency its line and core losses are higher than the normal line frequency transformer. Reducing the current density in copper wire can reduce copper losses. The core loss increases with increasing frequency. They can be reduced by reducing flux density. Also lower flux density insures operation in linear region. Thus to reduce core loss flux density should be chosen less than that of the line frequency transformer.

3.4.2 Passive Harmonic Filter

Rating of the Passive harmonic filter capacitor should be carefully determined. In most cases the failure of the passive harmonic filter is due to incorrect rating of capacitor. This capacitor should be rated taking into consideration factors discussed in Section 1.2. Apart from these factors filter capacitor is subjected to very high amount of harmonic stresses. Harmonic currents, which may flow, should be calculated. Taking these currents into account internal fuse rating should be calculated. Capacitor units should be able to withstand these harmonic stresses. Series connection of inductor makes voltage across capacitor to rise. While designing capacitor this fact should be taken into account. kVAR rating corresponding to this "voltage boost" is calculated and the capacitor is rating is calculated accordingly. Inductor should be "harmonic filter duty" with low losses. Losses in harmonic filter are very critical. As power quality improvement devices do not directly increase the production, higher losses will make the equipment less acceptable to the customer. Inductors used are normally dry type air cored AN (air natural) cooled.

CHAPTER 4

SIMULATION RESULTS

In this chapter simulation results of the hybrid filter scheme described in previous chapters of this thesis are discussed.

4.1 THE STUDY SYSTEM

The study system used for this simulation is shown in the Fig. 4.1. It consists of a 440 volts three phase source supplying the three-phase load of 500 kW. This load has uncompensated power factor of 0.8 (lagging). A fixed balanced star connected R-L load represents the load and harmonics are modeled current sources. Current harmonic contents are shown in Table 4.1. It is seen that THD of load current is 24.7 %. Load current waveform is shown in Fig. 4.2.

A 200 kVAR capacitor bank is provided as 5^{th} harmonic filter and 50 kVAR capacitor bank is provided as 7^{th} harmonic filter. It is assumed that due to passive filter component tolerances and parameter changes the 5^{th} and 7^{th} harmonic filters are mistuned. For parameter change of +10 %, tuning factor for 5^{th} harmonic filter is 4.5 while that for 7^{th} harmonic filter is 6.4. The quality factor of both the passive filters is assumed to be 20. The parameters of passive filters are given in Table 4.2. After installing this passive filter the power factor will improve from 0.8 to 0.97. The PCC voltage and source current waveforms are shown in Figs. 4.3 and 4.4 respectively. The harmonic contents of PCC voltages and source current are shown in Table 4.3 and Table 4.4 respectively.

For SCR of 5.5 the IEEE 519 individual current harmonic limit is 4 % and for current THD it is 5% (please refer Table 2.3). Thus using only the passive filter the IEEE 519

limit is exceeded. The hybrid active filter for 5th harmonic is installed to comply with the IEEE 519 standard. 7th order hybrid active filter is also additionally installed to check its performance and to further reduce the 7th order harmonic.

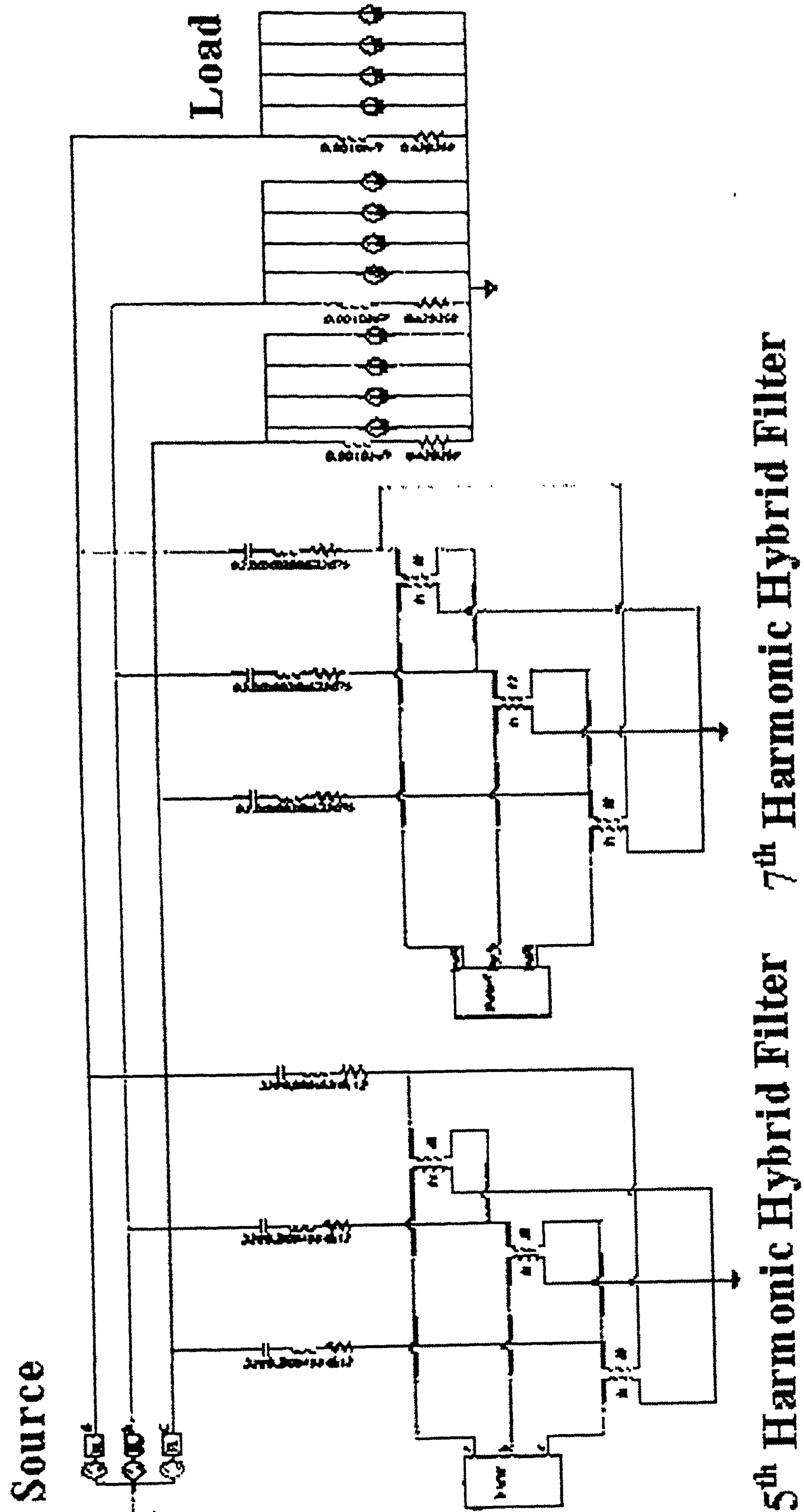

Fig. 4.1 The System Under Study

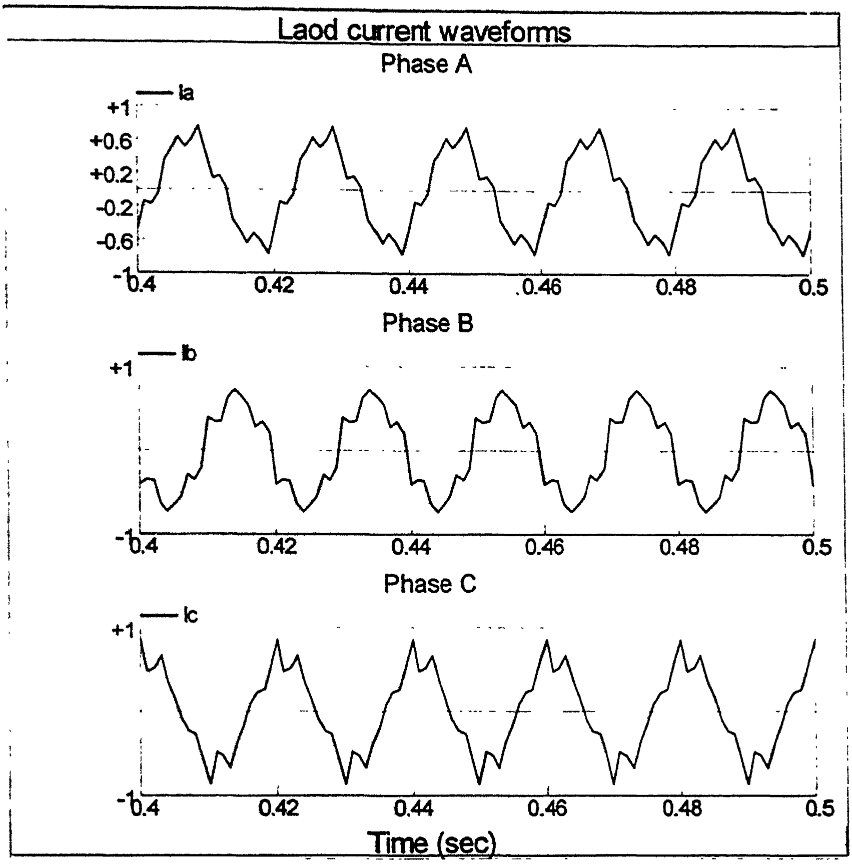

Fig. 4.2 Waveforms of the current drawn by the load

Table 4.1 Load current harmonics.

Harmonic Order	1	5	7	11	13
Magnitude	0.46235	0.091	0.064	0.02	0.016
Current THD = 24.7 %, Short circuit ratio at the PCC is 5.5.					

Table 4.2 Passive filter parameters.

	Resistance	Inductance	Capacitance
5^{th} order harmonic filter	0.12 Ω	0.15216 mH	3288.30 μF
7^{th} order harmonic filter	0.032075 Ω	0.29167 mH	822 μF

Table 4.3 PCC Voltage harmonics with passive filter only.

Harmonic Order	1	5	7	11	13
Magnitude	0.248	0.009307	0.00388	0.00380	0.00360
Voltage THD = 4.58 %					

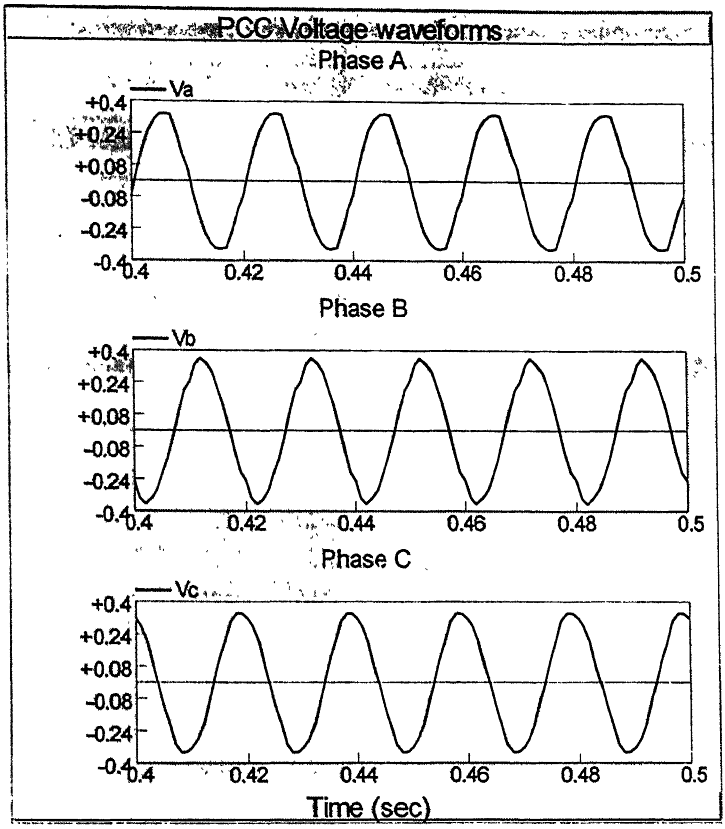

Fig. 4.3 Waveforms of the voltage at PCC with passive filter only.

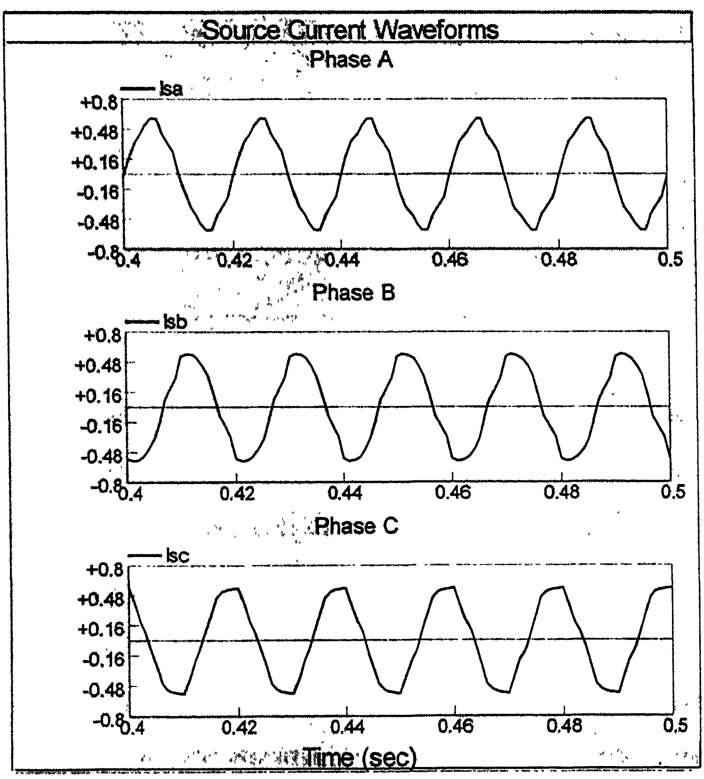

Fig. 4.4 Waveforms of the source current with passive filter only.

Table 4.4 Source current harmonics with passive filter only.

Harmonic Order	1	5	7	11	13
Magnitude	0.4085	0.0257	0.00933	0.00816	0.007546
Current THD = 7.225 %					

4.2 HYBRID ACTIVE FILTER

4.2.1 Implementation of Synchronous reference transform

The inverter structure used for the hybrid filters is shown in Fig. 4.5. Since the inverters must supply only balanced voltages, this three-phase structure is sufficed for the purpose.

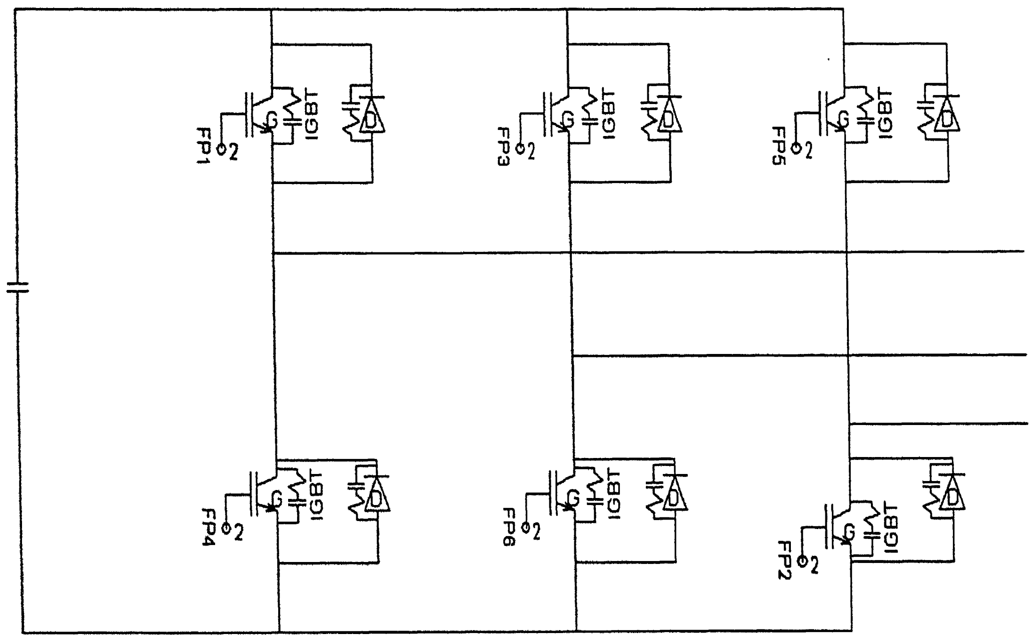

Fig. 4.5 Inverter used for hybrid filter.

PSCAD simulation drafts in Fig. 4.6 show how the synchronous transformation is achieved. This transformation require functions sin θ and cos θ. The phase angle θ is the voltage phase angle. This angle is obtained using a Phase Locked Loop (PLL) shown in Fig. 4.7. This angle is multiplied by -5 for SRF transformation at 5th harmonic. Then unit phasors are obtained from this multiplied phase angle (th5). The draft of Fig. 4.6 shows the simulation of the transformation matrix of equation (2.20). Signal is multiplied by this matrix and then filtered through a low pass Butterworth of

order 3 to get the signal in synchronous frame rotating at 5^{th} harmonic frequency. It may be noted that since the quantities obtained through the SRF transformation are DC, phase lag introduced by the Butterworth filter does not affect the results in steady state. This transformation is applied to voltage at PCC and currents through passive filter branches.

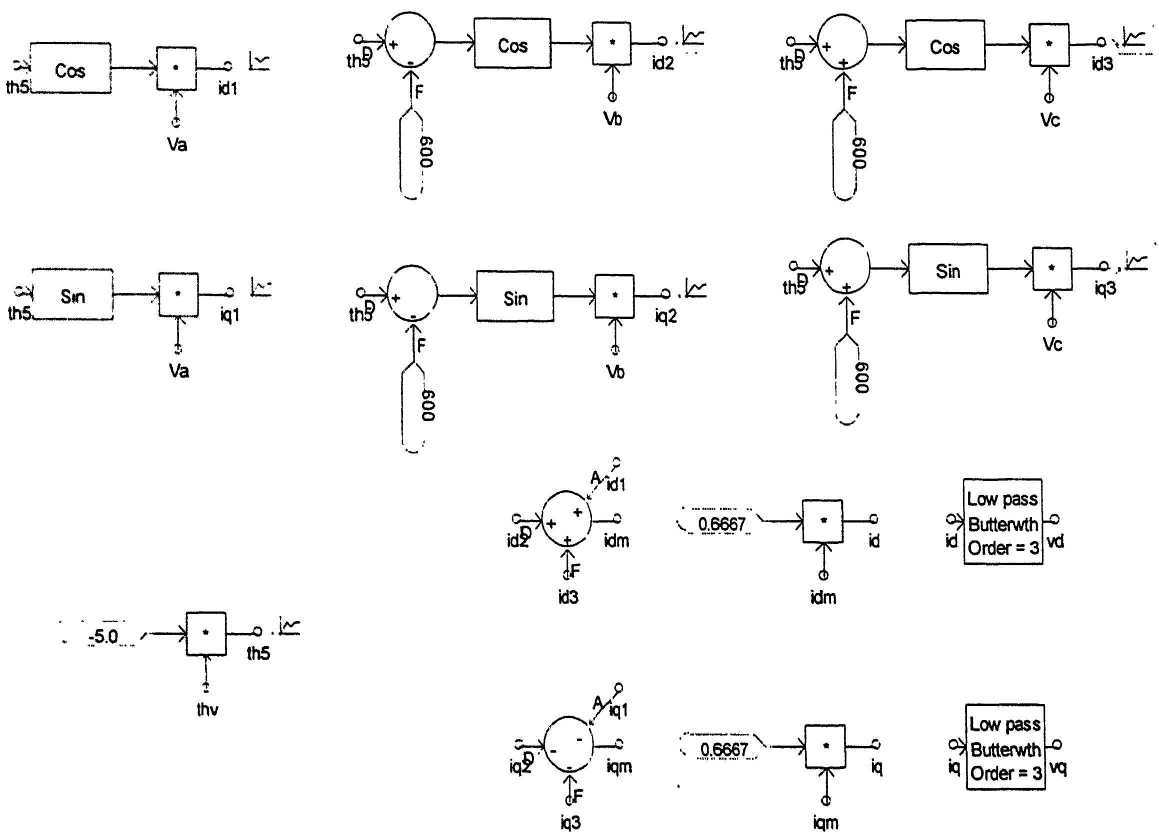

Fig. 4.6 Simulation draft showing implementation of SRF transform.

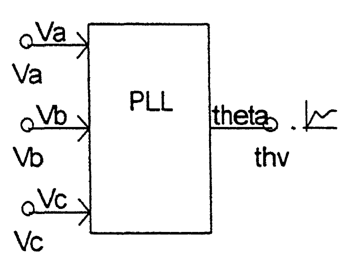

Fig. 4.7 Phase Locked Loop.

4.2.2 Calculation of the required DC bus voltage

Using the equations in section 3.3 The DC bus reference voltage for 5^{th} and 7^{th} harmonic filter is calculated as shown in simulation draft of Figs. 4.8 and 4.9. Please

note that change of sign in addition block in the calculation of d and q axis voltage command for the 5th and 7th harmonic filter. This is due to negative and positive sequence nature of 5th and 7th harmonic respectively. Computed reference DC bus voltages are shown in Fig. 4.10 (a) and (b).

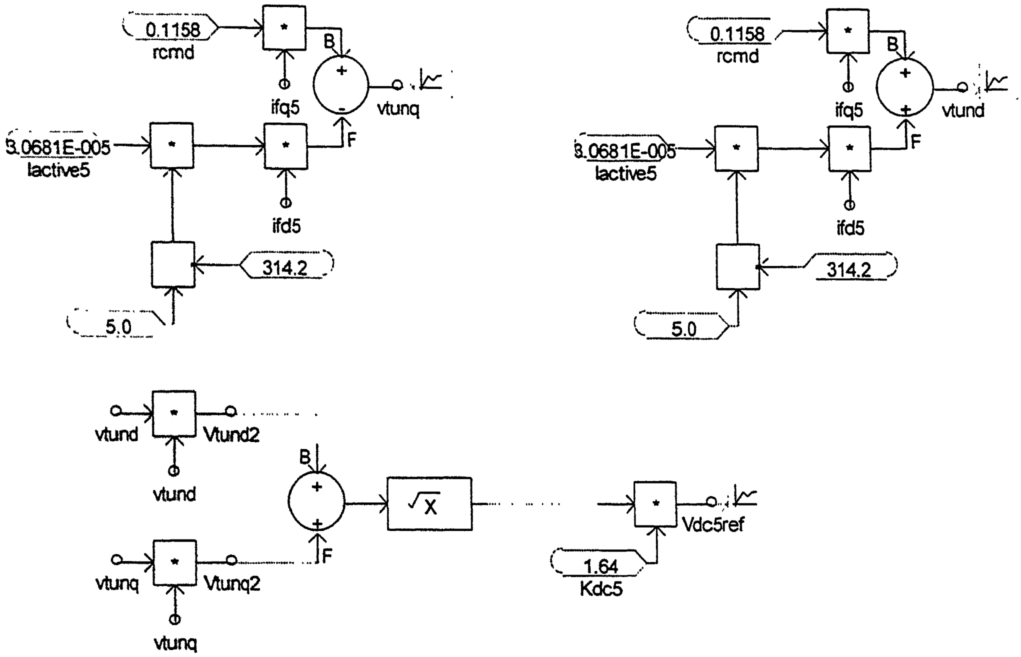

Fig. 4.8 Calculation of DC bus voltage reference for 5th harmonic hybrid filter.

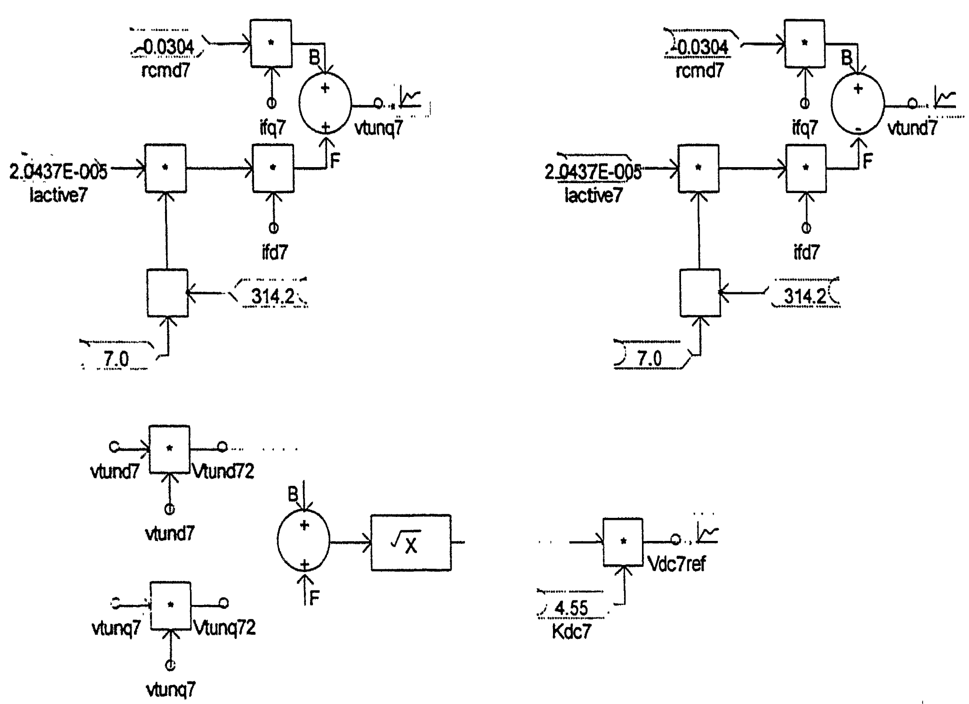

Fig. 4.9 Calculation of DC bus voltage reference for 7th harmonic hybrid filter.

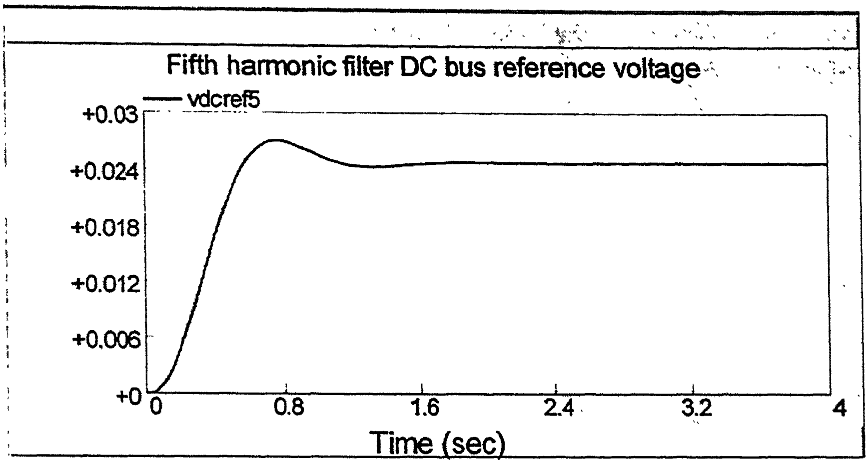

Fig. 4.10 (a) Reference command for the 5th harmonic hybrid filter.

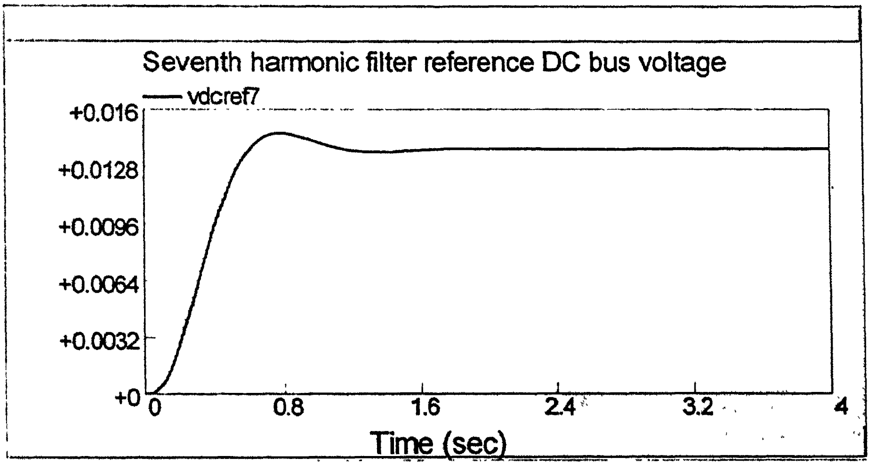

Fig. 4.10 (b) Reference command for the 7th harmonic hybrid filter.

4.2.3 Inverter and its firing circuit

Inverter used in the hybrid filter is shown earlier in Fig. 4.5. Parameters of the IGBT switches used for this inverter are given in Table 4.5.

Simulation draft of the inverter firing circuit is shown in Fig. 4.11. This block calculates the firing pulses and the interpolation time required for interpolated turn-on of the IGBTs. The Pulse Width Modulation scheme is shown in Fig. 4.12. Three triangular waves, which are phase shifted from each other by 120° are compared with the sine wave. The firing pulses are generated such that no two switches in the same leg are ON at the same time.

Table 4.5 IGBT parameters.

Parameter	Value
Thyristor ON Resistance	0.01 ohm
Thyristor OFF Resistance	10^{6} ohm
Forward Voltage Drop	0.1 V
Forward Breakover Volts	5 kV
Reverse Withstand Voltage	5 kV
Minimum Extinction Time	0.001 μsec
Snubber Resistance	500 ohm
Snubber Capacitance	25 μF

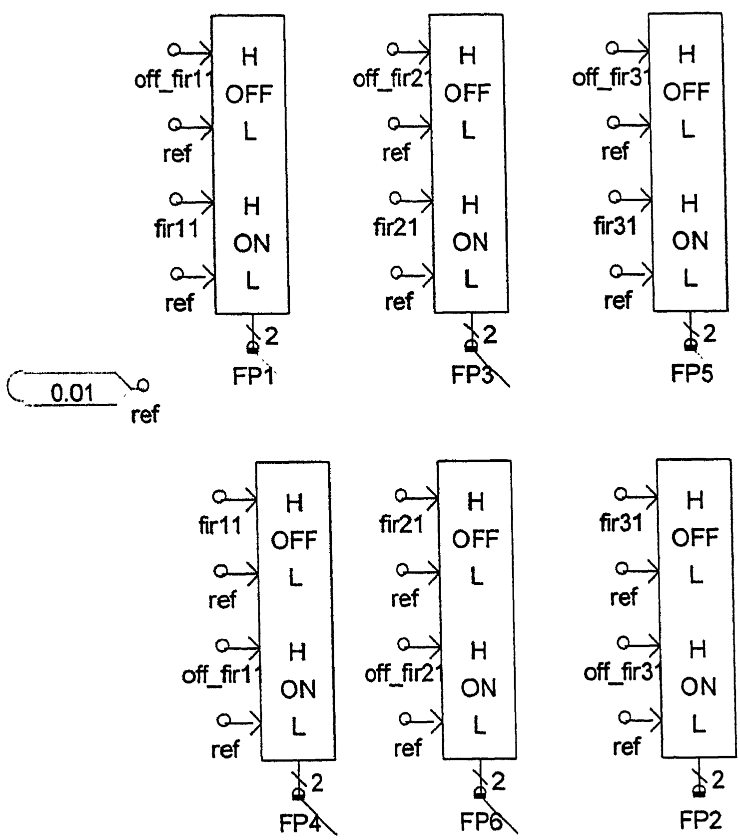

Fig. 4.11 Firing pulse generation for the inverter.

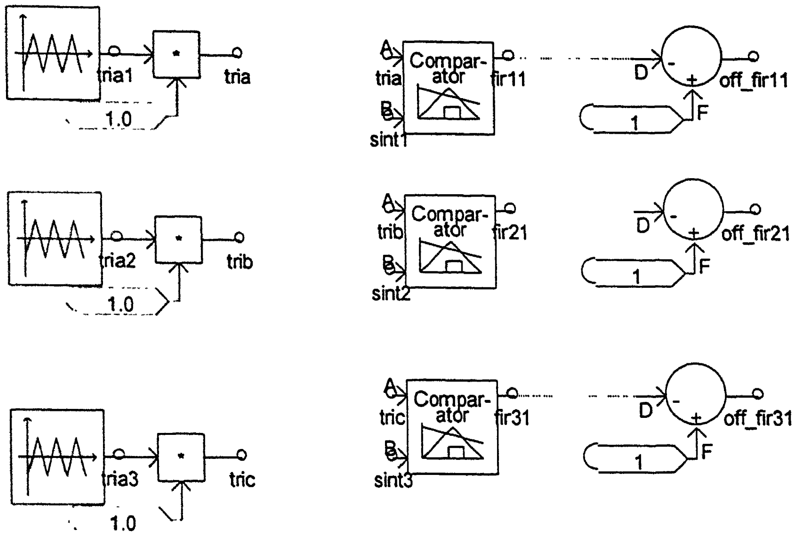

Fig. 4.12 PWM for the inverter.

4.2.4 DC bus capacitor voltage controller

The DC bus capacitor voltage is maintained using the PI controller shown in Fig. 4.13. The DC bus capacitor voltage is measured and it is filtered through a 3rd order low pass Butterworth filter. Error of filtered and desired DC bus voltage is given to PI controller. The output of the PI controller controls the phase angle of the fundamental frequency sine wave. Required power flow for maintaining the desired DC bus voltage is done at fundamental frequency. The phase angle of the fundamental sine wave will govern the power flow. The DC bus capacitor voltage waveform for 5th and 7th harmonic filters are shown in the Fig. 4.13 (a) and (b). Fig. 4.15 shows the output voltage waveform of the active filter inverter.

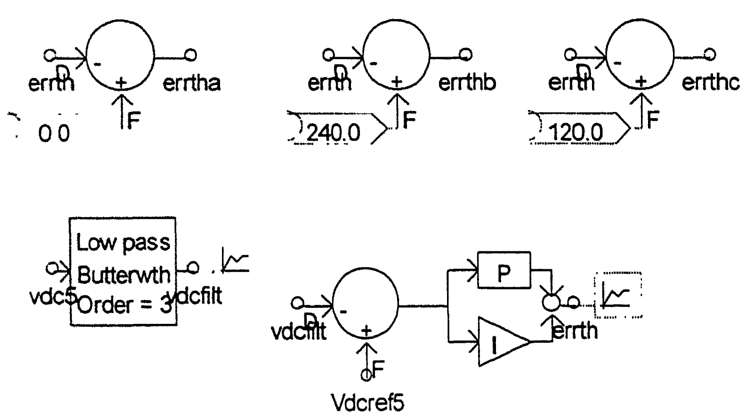

Fig. 4.13 PI Controller.

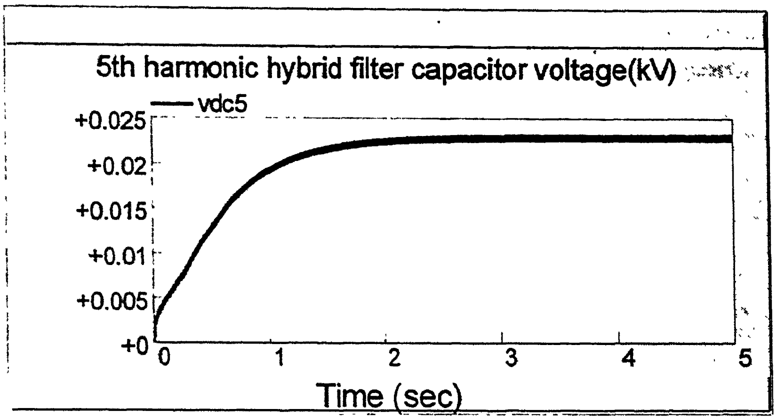

Fig. 4.14 (a) 5th harmonic hybrid filter DC bus capacitor charging waveform.

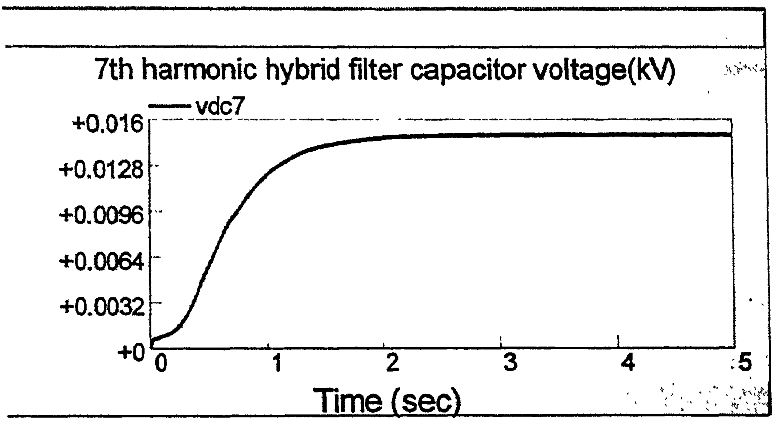

Fig. 4.14 (b) 7th harmonic hybrid filter DC bus capacitor charging waveform.

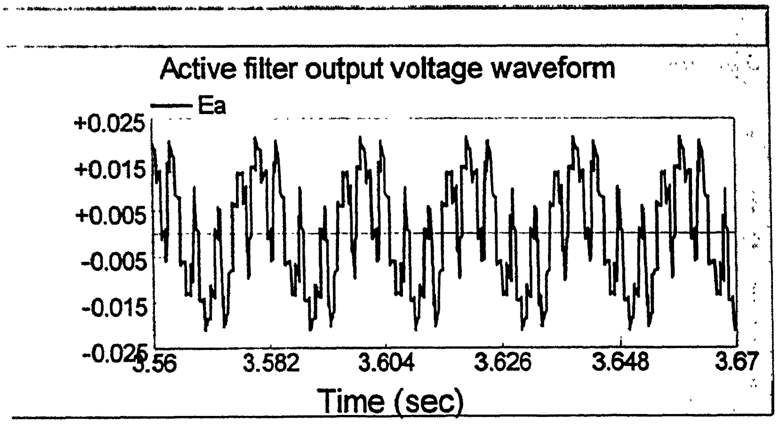

Fig. 4.15 Phase to neutral output waveform of the inverter.

4.3 SYSTEM PERFORMANCE WITH HYBRID ACTIVE FILTER

For SCR less than 20 the IEEE 519 individual harmonic limit is 4% and for THD it is 5% (please refer Table 2.3). Thus using only the passive filter the IEEE 519 standard is not satisfied. Waveforms of source current and voltage at PCC after installing hybrid active filter are shown in Figs. 4.16 and 4.17. The system current and voltage harmonics after installing the hybrid active filter are shown in Tables 4.6 and 4.7 respectively.

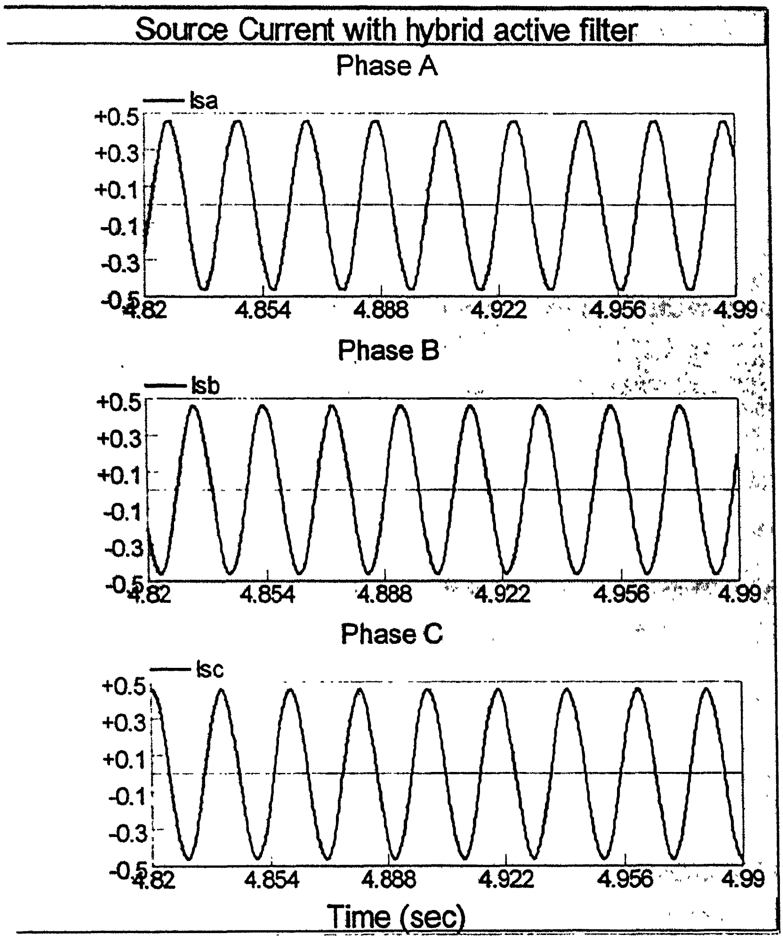

Fig. 4.16 Source current waveforms with hybrid active filter.

Table 4.6 Source current harmonics with hybrid active filter.

Harmonic Order	1	5	7	11	13
Magnitude	0.4618	0.000702	0.0019	0.00457	0.0035
Current THD = 1.32 %					

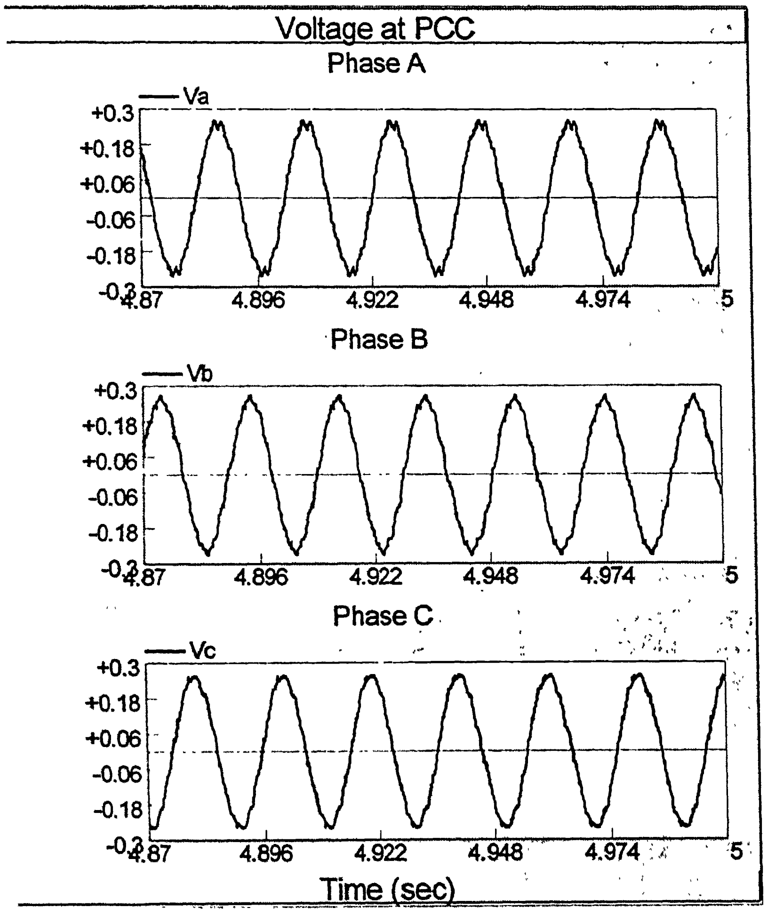

Fig. 4.17 Voltage waveforms at PCC with hybrid active filter.

Table 4.7 PCC Voltage harmonics with passive filter only.

Harmonic Order	1	5	7	11	13
Magnitude	0.2547	0.0037	0.00114	0.00853	0.00217
THD = 3.77 %					

Thus as it can be seen from above figures in Table 4.6 and 4.7 the harmonic levels are well within the limits after installing the hybrid filter. The slightly higher order harmonics are found in the results obtained. These can be reduced using high pass

filters. But IEEE 519 is satisfied at PCC. It can be noted from this scheme, the inverter rating will be very small, as its output will be dominantly harmonic with low fundamental frequency component. In this simulation study the three-phase kVA rating of the inverter is 17.6 which is around 2.5 % of the load rating.

CHAPTER 5

CONCLUSIONS

A dominant harmonic switching inverter is connected in series with the passive filter to improve its performance. This inverter uses modified pulse width modulation. In this PWM scheme triangular wave has a frequency of the dominant harmonic which will decide the switching frequency of the semiconductor switches. Thus small bandwidth inverter is required for this scheme. This triangular wave is compared with the sine wave. Modulation index in this PWM scheme is kept very small depending upon the required DC bus capacitor voltage. Reference voltage of the DC bus is calculated in synchronous reference frame rotating at dominant harmonic frequency.

5.1 GENERAL CONCLUSIONS

General conclusions drawn from this thesis are as follows:

- Mistuning of the passive filter due to capacitor and inductor tolerances, change in parameters due to temperature variations, aging etc. lead to change in filtering characteristic of the passive filter. Also danger of harmonic amplification restricts the designer from tuning the passive filter sharply to the desired harmonic frequency. This scheme overcomes above stated limitations of the passive filters.

- In this thesis it has been shown that using the Synchronous Reference Frame (SRF) based hybrid active filter harmonic contents in supply current are significantly reduced thereby IEEE 519 is satisfied at Point of Common Coupling (PCC).

- Active filter inverter of this scheme is having output voltage proportional to dominant harmonic voltage. This voltage is considerably lower than fundamental

voltage. This fact gives rise to significant reduction in size of the active filter inverter. This will obviously reduce the cost of the harmonic filtering. In the simulation case size of the non-linear load is 650 kVA. Three-phase kVA of the active filter that was used in this scheme has a size of 17.6 kVA. Thus around 2.5 % rating of the active filter is required.

- The inverter used in this hybrid active filter does not require any external energy source. DC bus voltage is maintained to the desired value by drawing power from the source at fundamental frequency.

- This switching frequency of this inverter is very low compared to other active filter inverters. The small bandwidth requirement is distinguishing feature of this scheme compared to other active and hybrid active filters schemes. This will lead to better efficiency of the inverter as high-frequency switching losses are reduced considerably.

- This scheme is suitable for high power applications. Stiff source reduces the effectiveness of the passive filter as less load harmonic current flows through the passive filter compared to that flowing into the source depending on the ratio of source impedance and passive harmonic filter impedance at that frequency. This scheme will effectively isolate harmonic producing load from the source.

5.2 SCOPE FOR FUTURE WORK

Some suggestions for future work are as follows

- Voltage rating of the inverter depends upon the transformation ratio of the coupling transformer. Some study may be done to optimize the size of the active filter and coupling transformer, which will give the most economic solution.

- In this thesis it is suggested that to avoid sinking of source side harmonics in the passive filter the current through it should be monitored. But this may lead to

reduction in filtering capacity of the hybrid filter. Some better option may be devised to overcome this limitation.

- Experimental setup for validation of the results obtained in this thesis should be developed.

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